Development of an Open Source Hourly Building Energy Modeling Software Tool

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Civil Engineering

Waterloo, Ontario, Canada, 2010

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Computer building energy simulations are an important tool in the design of low-energy buildings. Building energy modeling is used to predict annual energy consumption, determine peak loads for sizing equipment, complete cost-payback analysis to select appropriate energy efficiency measures, and show compliance with standards. While energy modeling is a cost effective tool to assist in design, there are a number of challenges in the current building energy modeling industry. Most energy modeling programs are too technical to be used by architects, and too complex for early design when many system parameters are not known. Programs that are easy to use lack accuracy and the ability to model new, innovative systems. Programs that allow the simulation of new systems are very complex and have a high learning curve for engineers.

In this thesis, a computer program that was developed to model building energy loads and energy consumption of mechanical systems is presented. The program, entitled “Building Energy and Loads Analysis” (BELA), has a transparent, open architecture to allow additions and changes, and it facilitates the simulation of simple early design and detailed later design. BELA is currently a simple, single-zone model but it could be expanded at a later date.

The program consists of two stages: the loads model and the systems model. In the loads model, users define a building through a series of inputs. The program uses these inputs to calculate the total heat transfer acting on the space, which is the total heating or cooling load on the space. The systems model calculates the total energy consumption of the building. These calculations are performed hourly for one year. Two heating and cooling systems models have been created, radiant heating and cooling, and fan coil units, both with a dedicated outdoor air system to provide ventilation. The output of the loads model can be used to view the loads on the buildings, and to view how enclosure design parameters such as amount of insulation or type of window affect the building loads. The output of the systems model shows the total energy consumption of the building for one year. It can be used to compare different mechanical systems and evaluate various design parameters within the systems.

The BELA program is used to create a natural ventilation model in order to demonstrate the implementation of an innovative system, and to compare the energy consumption of a naturally ventilated building to a mechanically ventilated building. The case study model showed that natural or hybrid ventilation can reduce building energy consumption when designed properly, however

when used incorrectly it can significantly increase energy consumption. For scenarios where opening sizes were not restricted to provide only the necessary airflow, energy consumption of natural ventilation was higher than with the dedicated outdoor air system. This was due to the increased space heating and cooling loads from excessive unconditioned air entering the building. When opening sizes were limited to provide only the required airflow rates and to take advantage of free cooling, energy consumption for a year was reduced by 3.5%. This simulation showed that natural ventilation may save a small amount of energy when designed correctly. However, designers should evaluate it concurrently with other energy efficiency measures that may provide greater energy savings.

Acknowledgements

I would like to thank my supervisor, Dr. John Straube, for his guidance and teaching throughout this project. Thank you to Joanne McCallum and Greg Sather of McCallum Sather Architects for their advice and financial support. Thanks to my fellow BEG students for a great office in which to talk and share ideas; Rachel, Peter, Nick, Ivan, Matt and Rob. Finally, thanks to my friends and family for a fun two years!

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Chapter 1
Introduction

As climate change, pollution and energy supply become more of a concern, it is important that society find ways to reduce energy consumption in all areas of society. According to the 2005 Energy Use Data Handbook, buildings accounted for 32% of total energy consumption in Canada in the year 2003, 2.639 PJ or $7.3x10^{11}$ kWh (NRCan 2005). It is clear that buildings consume a significant amount of energy, and it is important that the building industry continues to work to reduce building energy consumption as new buildings are designed and constructed.

The average Canadian office building in 2005 had an energy intensity of 444 kWh/m^2 (NRCan 2004), though modern, low energy office buildings can consume less than 100 kWh/m^2. There are many common energy efficient measures that can be employed to reduce energy consumption in new buildings to realize these low energy buildings. For example, some common energy efficiency measures include: higher levels of insulation, better insulating windows, enclosures without significant thermal bridges, efficient mechanical systems, heat recovery, and renewable energy systems. Many energy efficiency measures have an added initial cost and the energy saved must be weighed against the project budget and payback period of the additional investment. Computerized building energy simulation models give designers a cost-effective tool to simulate the energy consumption of a proposed building and predict the energy savings that would be realized from the energy efficiency measures being considered. Designers can use this information to calculate payback periods and select the energy efficiency measures appropriate for their project. Energy modeling has become an important part of many residential and commercial building projects. However, there are a number of challenges with most current building energy modeling tools.

In practice, the design of a new building requires input from many consultants with multidisciplinary skill sets. Although many members of the design team effect the energy consumption or energy efficiency of a building, it is not clear who is responsible for ensuring a low energy design.

Figure 1-1 shows a traditional organizational structure of a new building design team. There is a client or project manager who establishes the requirements for the building. This group hires an architect, who organizes a team of engineers and consultants. The architect is generally responsible for creating the building layout and designing the enclosure, as well as managing all sub-consultants. Consultants usually include a site/civil engineer, structural engineer, mechanical engineer, electrical engineer, and other parties as necessary. Energy modeling is normally performed by either a mechanical engineer or another consultant hired specifically for modeling. Some projects may also include a "green building" consultant responsible for energy efficiency and other environment-related issues.

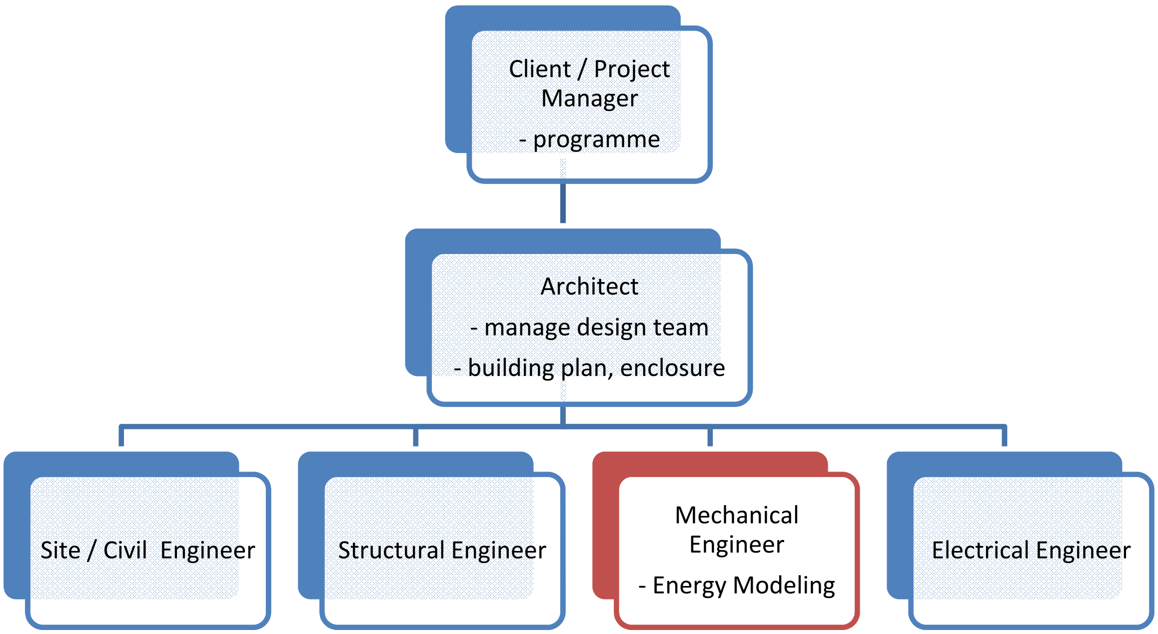


Figure 1-1: Traditional building design team structure.

The desire for a low-energy building usually must begin with the client or project manager, and be passed along to the architect and design team. The client typically does not have the knowledge and expertise to create a low-energy building, this must be the responsibility of the designers. Within the design team, the design decisions by the architect and nearly all consultants affect the energy performance of the building. However, in most cases only the mechanical engineer or modeling engineer completes energy simulations. To achieve a low energy building, this organizational structure requires excellent communication between groups, particularly at the initial design stages. Consultants must provide good information to the modeler, and the modeler must provide prompt feedback on simulation results.

To inform decisions on orientation, building shape, window area, and so on, the architect requires prompt information from the energy modeler, early and often. Later in the process, the mechanical systems designer also uses energy modeling to inform their design. All parties must coordinate their energy efficiency measures to design an optimal building. Though architects are often responsible for managing the design team, most energy modeling programs require a person with more technical understanding such as a mechanical engineer. One drawback of current energy modeling programs is that they usually cannot be used by an architect and thus the benefits of modeling are not gained during the initial, highly iterative conceptual design stage.

The relationship between the architect and the mechanical engineer is a particularly important one with respect to energy consumption. Architects design the enclosure systems that define the loads on the building. Mechanical engineers design the heating, cooling and ventilation systems to meet the loads. In other words, architects are responsible for loads while mechanical engineers are responsible for systems energy. A poor architectural design will force high mechanical systems energy, while a poor mechanical design will spoil energy savings from good architectural design.

The distinction between loads and mechanical systems energy is important. The load on a building space is the total instantaneous heat transfer that occurs to or from that space. Loads may be created by heat loss through a wall from conduction, air leakage through cracks in the enclosure, heat gain from solar radiation through a window, and other heat sources (for example lights and equipment) in the space. System energy is the amount of energy consumed by the mechanical equipment to offset the heating or cooling load. For example, system energy may consist of the energy to power a boiler, fans and pumps to generate and distribute heating to a space. Since none of the mechanical systems that produce or distribute heat in this example are 100% efficient, the system energy will always be more than the heating load.

Loads are quite predictable during early design stages as they are governed primarily by the building enclosure, which is typically designed by the architect. Accurate calculation of systems energy requires detailed knowledge of the HVAC systems, which is often not known until later design stages. From an energy modeling standpoint, it is useful to model and provide feedback on loads and systems separately so that early design decisions can be evaluated based on how they affect the loads on the building, without being complicated by uncertain systems parameters. This is another drawback of many energy modeling programs; some do not output loads separately from systems. Though, it should be noted that when the building parameters are well known it is beneficial to combine loads and systems as the HVAC system may impact the building loads. For example heat produced by fans and pumps will add to the cooling load on a space. These effects are negligible in early design stages.

Though most energy modeling programs are too complicated for architects and require many assumptions in early design stages, they also present challenges even for knowledgeable engineers. There is always a tradeoff between accuracy and complexity in modeling programs; more accurate programs tend to be difficult to use, while easy to use programs are less accurate and may not have the capability to model a wide range of systems. A number of modeling programs allow users the flexibility to create new systems models for innovative, emerging, one-off systems. However, this often comes with a high learning curve, even though the mathematical calculation of these systems' energy consumption may be straightforward, as users need to learn the program code. On the other hand, programs that are extremely popular due to their ease of use often require workarounds or hand calculations for newer, more efficient systems.

The most common existing modeling programs pose a number of challenges to design teams in the effort to create low energy buildings. They cannot be used by most architects and therefore require significant communication between design team members. Most programs do not facilitate early, high-level design, and often do not provide clear feedback on load energy. Easy to use programs that are popular in industry cannot handle new, innovative systems. Programs that can simulate innovative systems are very complex and have a high learning curve.

An example that illustrates the challenges of current, common energy modeling programs is the simulation of natural ventilation. Natural ventilation design facilitates air movement though a building driven by natural phenomena (wind and buoyancy effects). Natural ventilation reduces or eliminates fan power energy to ventilate a building, and may also reduce energy used for cooling. Natural ventilation must be carefully implemented in cold and humid climates to avoid excess energy consumption and comfort problems due to infiltration of cold or hot, humid outdoor air. Many cold-climate buildings that claim to make use of natural ventilation have standard mechanical ventilation systems supplemented by operable windows for use when outdoor weather is comfortable. There is often no quantitative analysis that goes into the design of naturally ventilated buildings, and therefore it is not known whether these designs provide useful ventilation or reduce energy consumption. Simpler building energy modeling programs are not capable of modeling natural ventilation. Some more complex models are, but require a high learning curve. Little work has been done to quantify the potential energy savings of natural ventilation.

An important step in the design of a low energy building is to simulate energy performance and determine which energy efficiency measures should be implemented. Current energy modeling software programs are too detailed for early design stages, too technical for architects, and do not easily facilitate the simulation of newer systems. This thesis will document a simple software program that models annual building energy consumption. The program, titled Building Energy and Loads Analysis (BELA), is Microsoft Excel spreadsheet based as this is a recognizable and almost universally available program that all engineers and architects know how to use. This thesis will document the design and engineering calculations used in the program. The program will be used to analyze and quantify energy savings from natural and hybrid ventilation through a series of case studies to demonstrate its application.

1.1 Objective

The objective of the research reported in this thesis is the development of a simple computer program or tool to model building energy loads and energy consumption of mechanical systems. The three primary goals of the program are to: (1) have a transparent, open architecture to allow additions and changes to systems, (2) allow for the separation of heating and cooling loads from mechanical systems energy use (thereby aiding the separate decisions made by architects and mechanical engineers), and (3) facilitate the simulation of simple early design and specialized or innovative systems in detailed later design.

1.2 Scope

The scope of the thesis is to create a program to accept user inputs describing in a simplified manner a proposed building design, and quickly calculate and report on heating and cooling loads and total energy consumption for the building. The program is intended for small to medium buildings that can be reasonably modeled as a single zone (that is, they have uniform temperatures throughout and do not have large heat gains or losses in any specific area).

The scope of this thesis is to document the equations and algorithms used in the program. The program is then used to demonstrate the analysis of the energy performance of an innovative system, natural and hybrid ventilation.

1.3 Approach

Figure 1-2 shows the thesis project approach. The thesis begins with a review of commonly used energy modeling software programs to examine the benefits and drawbacks of these programs and determine important features of a simulation program.

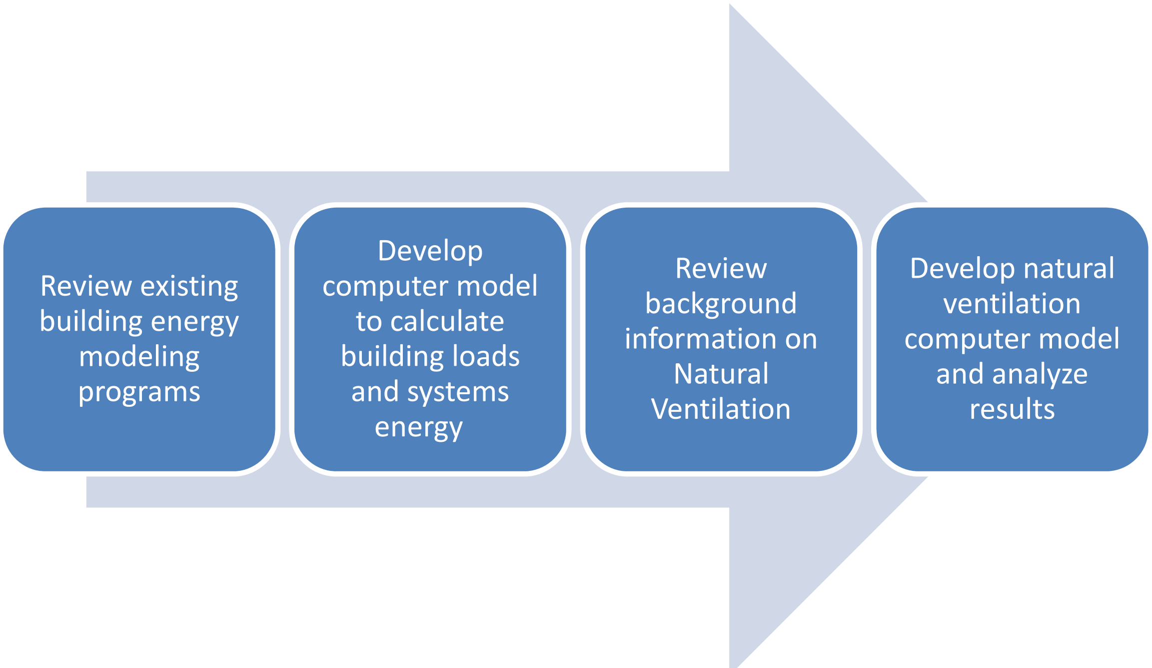


Figure 1-2: Thesis project approach.

The thesis follows with documentation of the building energy modeling program developed for this project. The documentation begins with an explanation of the loads model. The loads model takes user inputs to define the building, and uses heat transfer physics to calculate heating and cooling loads that act on the building space. The output of the loads model is compared to output from the program DOE2 to demonstrate that the model provides reasonable results. Following the presentation of the loads model, an explanation of the mechanical systems models is presented. Systems models are developed for two common heating and cooling systems, using the results of the loads model to calculate the total building energy consumption.

Following documentation of the program, a natural ventilation model is used to demonstrate an application of the program's specialized system capability. Background information on ventilation is first presented. The natural ventilation model is explained, and analysis is performed on the energy consumption of a natural ventilation system compared to an efficient mechanical ventilation system.

1.4 Organization of the Thesis

Chapter 2 contains a discussion on methods of calculating building energy consumption plus a review of a selection of commonly used building energy modeling programs. The programs reviewed are

DOE-2, TRNSYS, ESP-r, SUNREL and HOT2000. The strengths and weaknesses of each program are discussed.

Chapter 3 describes the loads model portion of the building energy modeling program that was developed. This chapter presents the user inputs required to calculate loads on the building space, the theory and calculations used to determine the loads, and the program output. Also in Chapter 3, the results of the loads model are compared to the output of the DOE-2 program used with the eQuest user interface.

Chapter 4 describes the mechanical systems model portion of the program. This chapter describes the user inputs required to calculate the total annual building energy consumption, the theory and calculations used to determine energy consumption, and the program output.

Chapter 5 presents background information on ventilation and particularly natural ventilation. Industry codes and standards related to ventilation are reviewed. Methods of calculating natural ventilation are presented. Existing computer programs that calculate natural ventilation are reviewed.

Chapter 6 presents a natural ventilation model case study. The simulations are described and results are analyzed to further understand possible energy savings of a natural ventilation system compared to an efficient mechanical ventilation system.

Chapter 7 provides conclusions and recommendations for future work.

Chapter 2
Building Energy Modeling Programs

Hundreds of programs have been developed to model building energy consumption. The United States Department of Energy provides a directory of information on 382 software programs related to building energy modeling (DOE 2006). Programs may focus only on certain components, such as window or wall systems, or programs may simulate whole building energy consumption. Whole building energy simulation programs will be discussed herein.

Energy modeling programs have the user define a building through a series of inputs. The program uses these inputs to calculate the loads on the building and the total building energy consumption, and outputs results. Two common types of calculations are commonly performed: annual energy use and peak design energy. Annual energy calculations determine the energy consumed over a one year period, often by calculating energy at time steps such as one hour intervals. Peak energy calculations determine the maximum energy that will be used by the building at any time, usually at the coldest winter heating day and warmest or most humid summer cooling day. Peak calculations are used for sizing mechanical equipment, while annual energy calculations are more often used for determining appropriate energy efficiency measures in the design of a low energy building. Annual energy calculations will be the focus of this project.

There are a number of different ways of estimating annual energy performance. Most simulation programs employ a time step of one hour (smaller time steps give better accuracy but increase computation time). The heat transfer load acting on the space is calculated at each time step, and the total system energy required to meet the load is calculated at each time step. The load calculation is complicated by thermal storage effects; heat may be stored in building components, known as "thermal mass", and released at later times. For example a concrete wall exposed to solar radiation during the day will store heat and release heat to the space at night when the sun sets. Methods of calculating annual energy consumption and accounting for thermal storage will be discussed in this section.

Many reviews of building energy simulation programs have been completed, for example Crawley et. al. (2005) and DOE (2006). A number of whole-building energy simulation programs will be reviewed here to examine the various methods of calculating energy use, and capabilities and limitations of existing programs. The programs selected for review in this study are DOE-2, TRNSYS, EnergyPlus, ESP-r, SUNREL, and HOT2000. These programs were selected as they are commonly used in the current building modeling industry, and they employ different methods of calculating annual energy consumption.

2.1 Energy Estimation Methods

The first step in calculating building energy consumption is to determine the loads on the building. Loads are instantaneous heat gains or losses that occur by conduction, convection, and radiation. Building loads can be summarized in the following categories:

- Conduction Through the Enclosure
- Infiltration
- Solar Heat Gain
- Internal Heat Gains
- Ventilation

Heat transfer acting on a building at any instant in time are simple to calculate based on heat transfer physics. However, load calculations are complicated by thermal storage effects. Though a building experiences a certain heating or cooling load at any given time, energy is stored and released by thermal mass in the building, creating a time delay on the load experienced by the heating, ventilating and air conditioning (HVAC) system. Most energy modeling programs employ similar methods of calculating instantaneous loads but differ in how they account for thermal mass time delay effects.

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE, 2007) has identified two primary methods of accounting for thermal mass in a building, the Heat Balance method (HB) and the Radiant Time Series method (RTS). There are also a number of older, less-accurate methods that are no longer recommended by ASHRAE but still used by some modeling programs, including the bin method and the transfer function method.

The HB method (ASHRAE 2007) is the most direct and accurate method of calculating heating and cooling loads, though it is complex and computationally intensive. In this method, a set of energy balance equations are created and solved for each surface in a building. Figure 2-1 shows a schematic of the components for the heat balance of each surface (ASHRAE 2007). The HB method is described in detail in ASHRAE Fundamentals 2007. The programs EnergyPlus and ESP-r use the HB method.

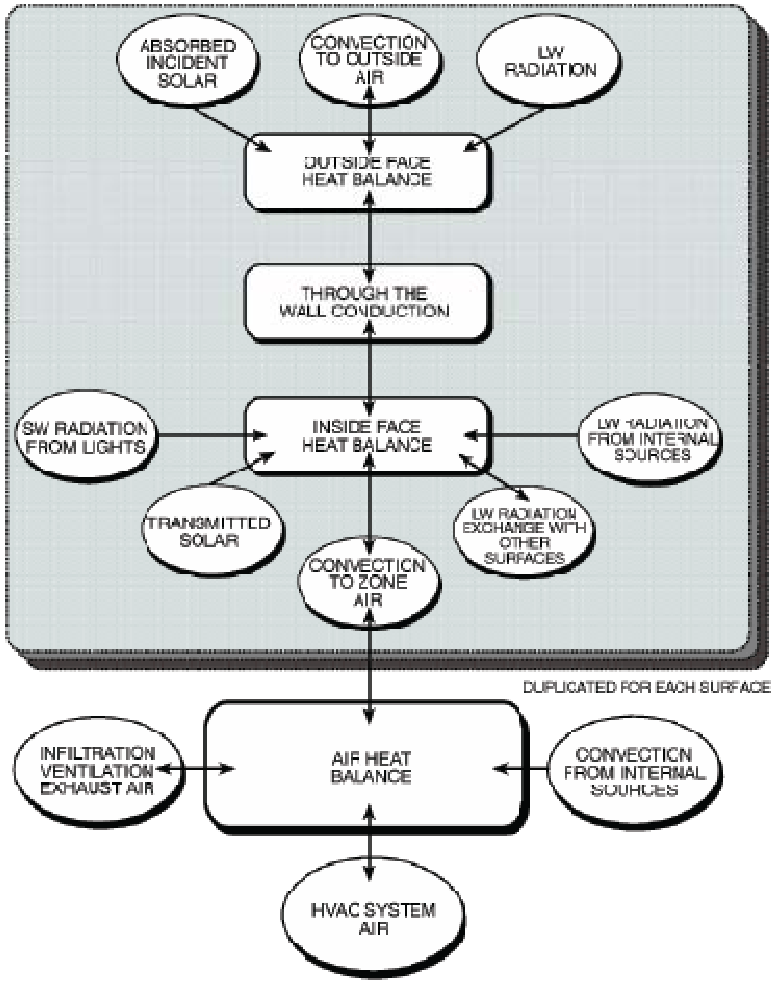


Figure 2-1: Schematic of the heat balance method (ASHRAE 2007).

The thermal network method (Deru 2002; McQuiston 2005) is a variation of the heat balance method where the building is divided into thermal zones, modeled as a series of nodes. Each zone represents a space in the building that operates on the same indoor temperature control. Zones experience heat transfer between the outdoors (and ground), the sun, and each other. At each time step, the thermal network method collects all energy flows from each zone air node to zone elements and calculates the new zone air temperatures. Thermal network models can be more complicated and computationally intensive than HB models. The program SUNREL uses a thermal network model.

The RTS method (ASHRAE 2007) is simpler and less computationally intensive than the HB method, though not as accurate. Figure 2-2 shows an overview of the RTS method (ASHRAE 2007). This method assumes that convection heat transfer affects the load instantaneously, while conduction and radiation heat transfer has a time delay. Each heat transfer mechanism acting on the space is separated into conduction, convection and radiation components. Weighting factors are then applied to the conduction and radiation components to account for time delays. Weighting factors are derived from the HB method and represent portions of past heat gains that impact the load for the current hour. The values of the weighting factors depend on the amount of thermal mass in the building construction. Some weighting factors are provided in the ASHRAE 2007 Handbook of Fundamentals, Chapter 18. This method is used by the program TRNSYS.

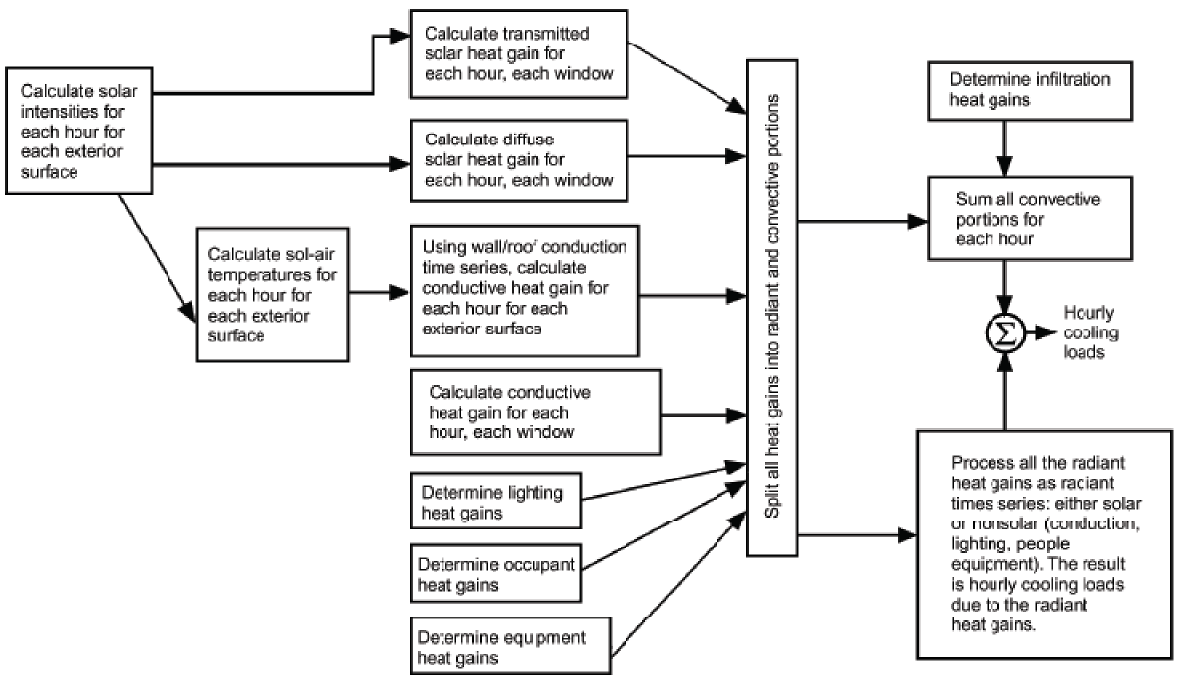


Figure 2-2: Outline of the Radiant Time Series method (ASHRAE 2007).

The Transfer Function (TF) method (ASHRAE 2007) is an earlier version of the RTS method that is still used in common energy modeling software programs. This method applies weighting factors directly to all conduction and radiation loads without splitting loads into radiation and convection components. This method is very simple to apply and still accurate for annual energy calculations, though it is not accurate for peak or hourly load calculations. The program DOE-2 uses the TF method.

The bin method (McQuiston 2005) is a very simple method of estimating annual building energy consumption. Weather data for a location is given in 5°F intervals or "bins", with the number of hours of occurrence of each bin. It is assumed that the building uses the same amount of energy for each outdoor temperature bin. A load profile is developed to determine the building energy consumption for each bin. The bin method does not include hourly thermal mass effects. The program HOT2000 uses the bin method.

2.2 DOE-2

DOE-2 was funded primarily by the United States Department of Energy to provide a free energy modeling software program. DOE-2 has been developed by James J. Hirsch & Associates (JJH) and Lawrence Berkeley National Laboratory (LBNL). This program has been in use for more than 25 years. Many user interfaces have been created for use with the DOE-2 engine, including eQuest (James J. Hirsch & Associates 2009) and the Canadian-built EE4 (NRCan 2008).

Figure 2-3 shows the structure of the DOE-2.2 simulation program (LBNL 2004). User inputs and weather data are used by the simulation engine in three stages: loads, HVAC and economics. The HVAC subprogram is further divided into systems and plant calculations. DOE-2.2 uses the transfer function method of calculating energy consumption. The engineering, physics and mathematics used in DOE-2.2 are documented in the DOE-2.1A Engineer's Manual (LBL 1982), though this manual is out of date. There is no up-to-date, public engineering manual for this program and so it is sometimes difficult to understand the calculation methods used in the program.

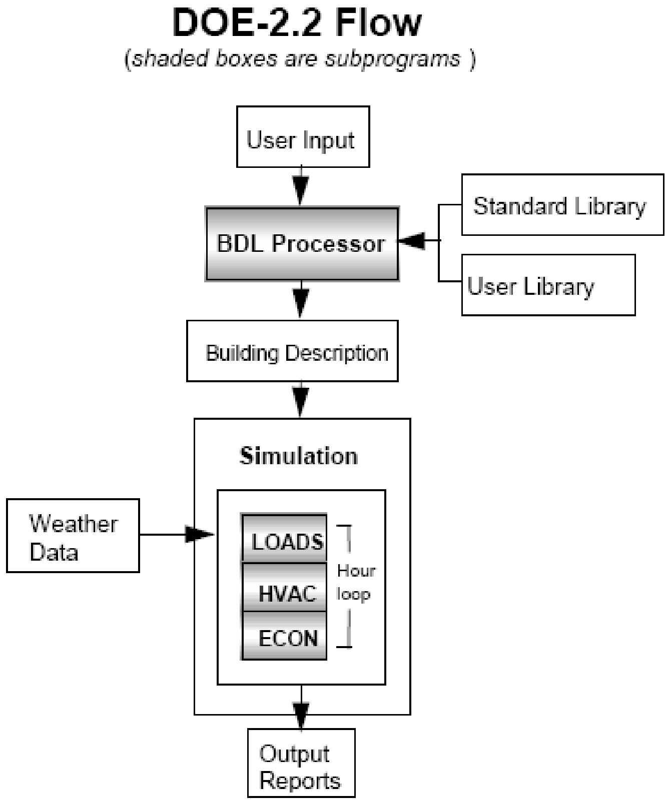


Figure 2-3: DOE-2.2 structure (LBNL 2004).

eQuest (James J. Hirsch & Associates 2009) is one user interface that was created to work with the DOE-2 engine. This program is likely the most commonly used energy modeling program in North America. eQuest steps users through the creation of a building energy model with a series of input screens that describe building geometry, enclosure, HVAC systems and plants. The program outputs a summary of the annual building energy consumption in clear, easy to understand graphs and also provides a detailed text file of output.

eQuest provides an easy to use interface with the full capabilities of DOE-2 but lacks the capability to model many newer system configurations. The eQuest shortcomings are particularly noticeable in the HVAC system definitions. Figure 2-4 shows a sample input screen from the design wizard for the HVAC system. The HVAC system must be selected from a handful of traditional systems. The program does not have the capability to model newer systems such as radiant heating and cooling, Dedicated Outdoor Air Systems (DOAS), chilled beam cooling, radiantly cooled ceilings, solar preheating, solar domestic hot water (DHW), and natural ventilation. It is common in industry to use workarounds or additional hand calculations to obtain approximate results for these systems.

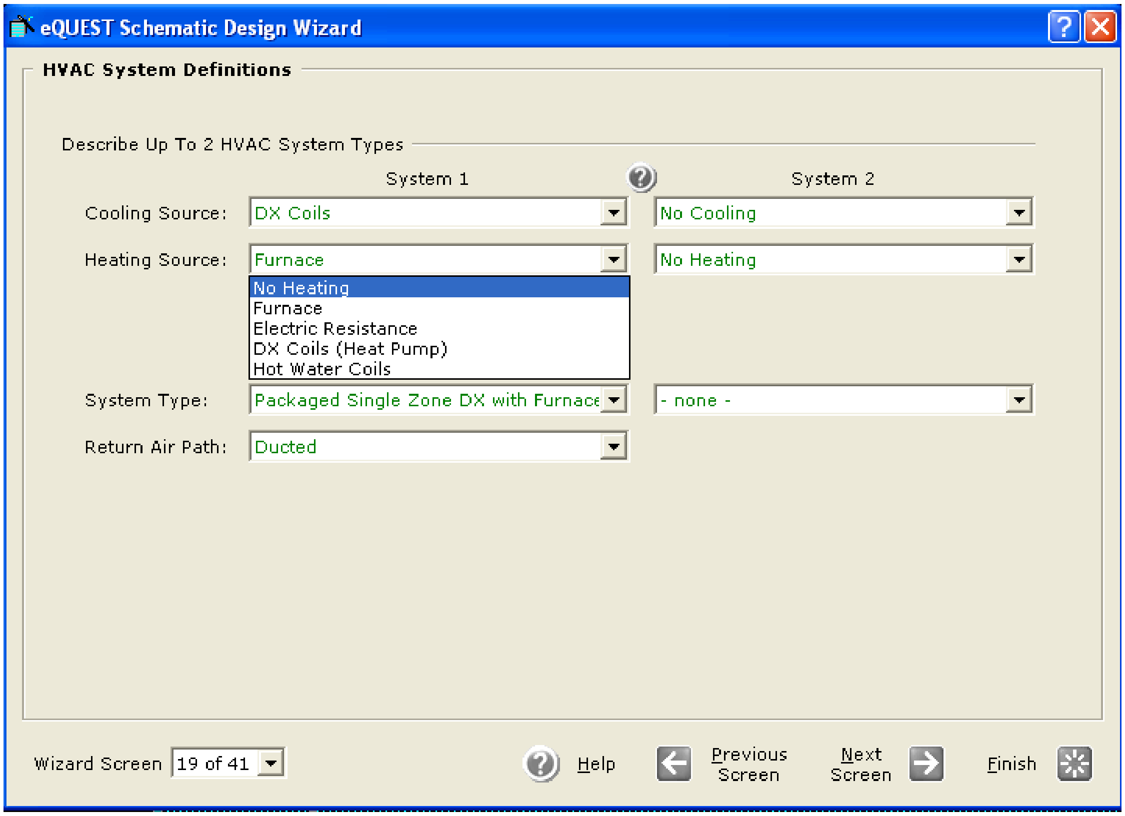


Figure 2-4: eQuest HVAC system input window.

Another DOE-2 interface is the Canadian-built program EE4 (NRCan 2008). This program was developed for designers to show compliance with Canada's Model National Energy Code for Buildings (MNECB). With EE4 , a building is created through inputs to a hierarchical tree, as shown in Figure 2-5.

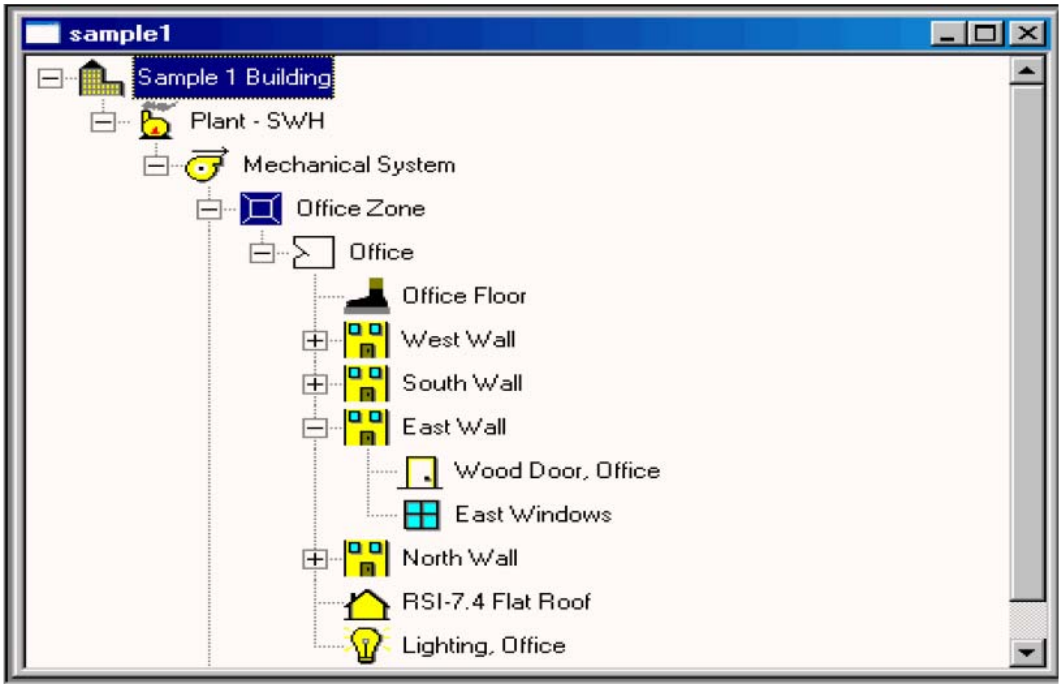


Figure 2-5: Sample EE4 building tree.

DOE-2 based programs like eQuest and EE4 are extremely popular in industry since they are easy to use and free. However, there is poor documentation for the calculations used in DOE2. The programs are limited in the systems that they can model and often require workarounds or hand calculations to obtain approximate results. The program also uses an out-of-date method of accounting for thermal mass, the transfer function method.

2.3 TRNSYS

TRNSYS (University of Wisconsin-Madison Solar Energy Laboratory 2006) was initially developed at the University of Wisconsin – Madison in 1975. This program models a building as a series of components, allowing users to access a library of pre-defined components or create their own components. TRNSYS is slightly more complex to use than DOE-2 based programs like eQuest, but allows users to model a significantly wider range of systems. New components can be created using common programming languages.

TRNSYS has a building creation wizard that makes the program quite useable; one does not have to create line code, though the wizard is more complex than the eQuest wizard. The higher level of complexity also gives users more control over the building model. Once a building has been created through the design wizard, TRNSYS displays the building as a series of components linked together (Figure 2-6). Users can then refine the components and relationships between components.

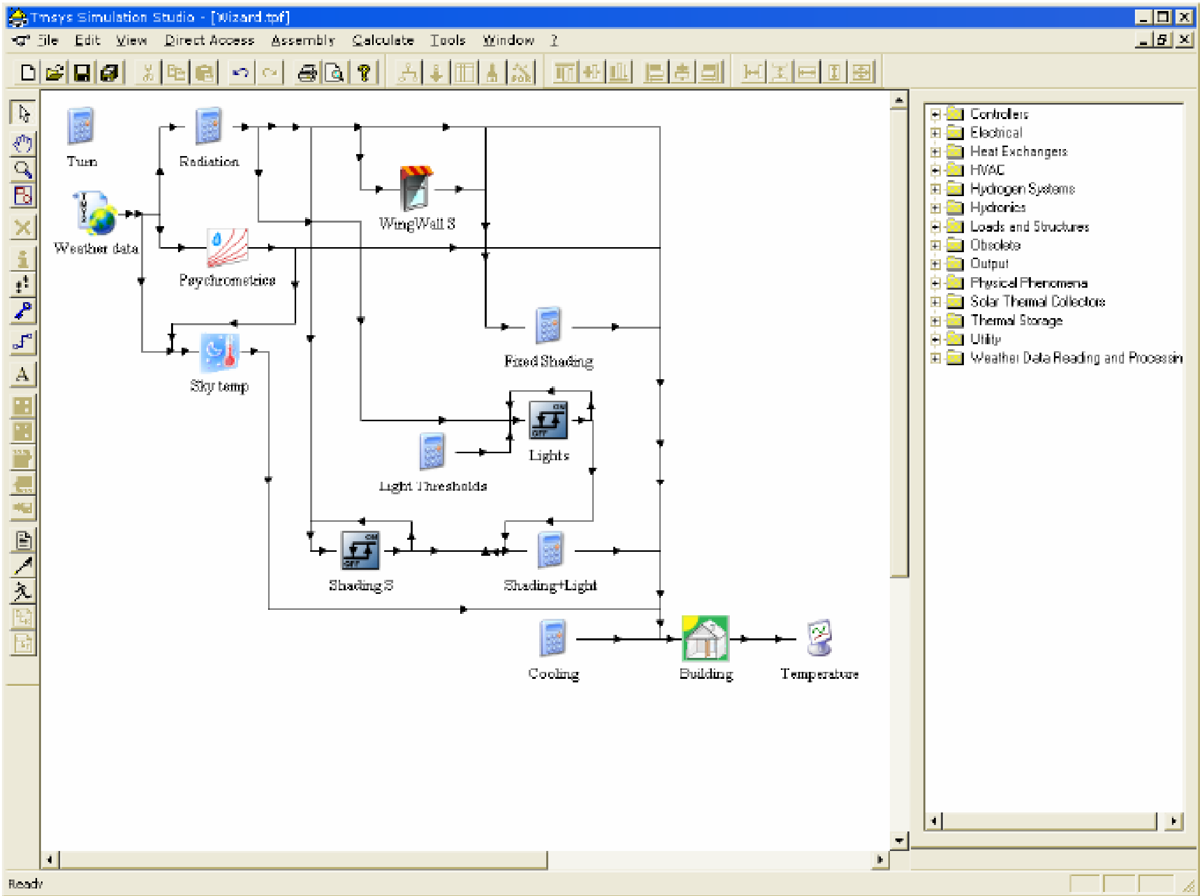


Figure 2-6: Sample TRNSYS building model.

TRNSYS uses the radiant time series method (RTS) to account for thermal mass by first dividing loads into radiative and convective components, then calculating ASHRAE transfer functions to apply weighting factors. As discussed previously, this method is more accurate than the simpler transfer function method used by DOE-2 but less accurate than the heat balance method used by other programs.

The TRNSYS library of components includes models for many different HVAC systems and parts of HVAC systems, allowing users to model far more systems than are available in DOE-2. Examples of components include different types of fans and pumps (including variable speed drive), thermal storage walls, solar thermal collectors, photovoltaics, heat recovery, and much more. TRNSYS can also directly model DOAS and various forms of radiant heating and cooling systems, unlike eQuest.

If a model is not available, users can create their own component models using common programming languages, though this would require the user to have some programming capabilities.

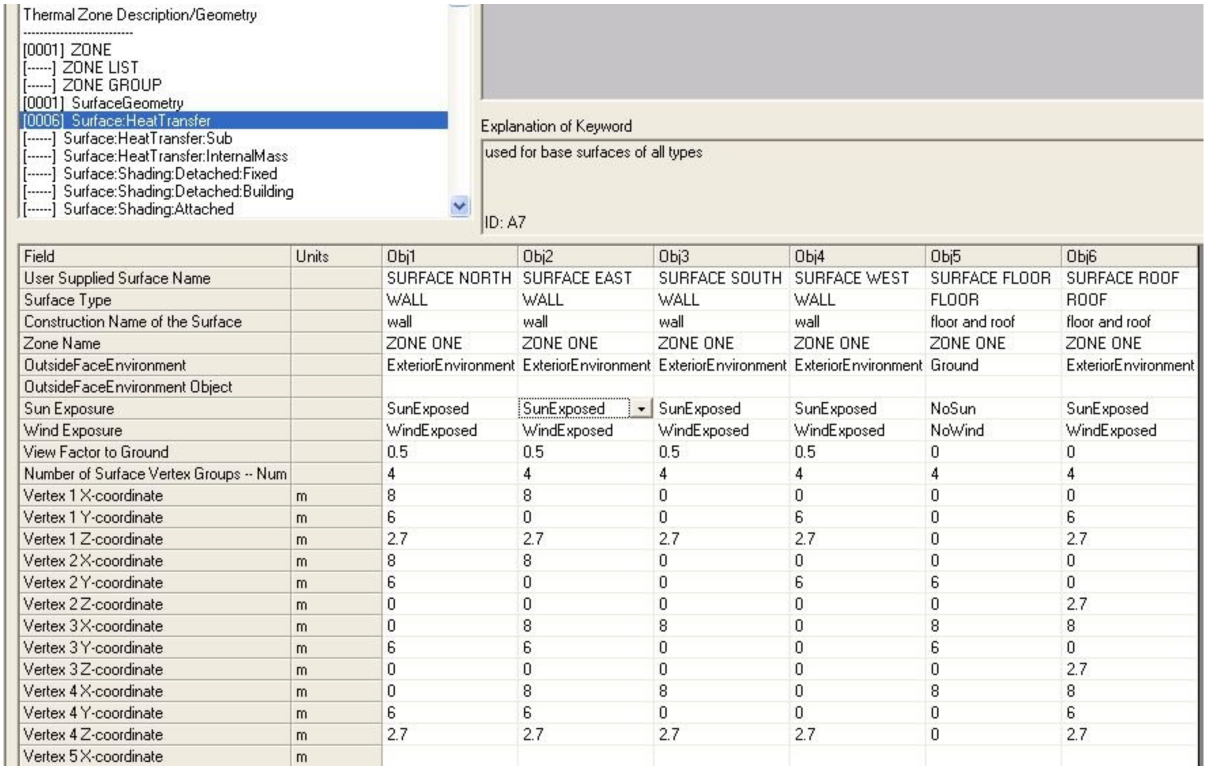
TRNSYS is more complex than DOE-2 based programs but still relatively easy to use, and with much wider modeling capabilities and higher accuracy than DOE-2 programs. Perhaps the greatest reason TRNSYS is not more commonly used in industry is its cost, where as many DOE-2 programs are available free of charge. The ability to add component models for whatever system is desired is one of the greatest features of TRNSYS.

2.4 EnergyPlus

EnergyPlus (University of Illinois 2009) was developed from two existing building energy modeling programs, BLAST and DOE-2, to improve upon certain deficiencies of these programs. Two important goals were to create a modular program to allow new systems to be added, and to integrate heat from HVAC systems into the building loads calculation. Like DOE-2, this program is open source and can be downloaded free of charge.

EnergyPlus is different from DOE-2 and TRNSYS in that it models loads and systems together. This improves the accuracy of simulations as heat gain from HVAC equipment is accounted for in the loads calculation. However, this also means users cannot view loads results independent of systems results. This is a positive when building parameters are well-known prior to modeling, including the HVAC and plant system parameters. Early in the design stage when many parameters are unknown, the simulation results may not be as useful.

The process of creating a new building model in EnergyPlus is more complicated than with DOE-2 and TRNSYS, though a number of user interfaces have been developed to simplify simulation. The building is defined by creating and linking together a series of objects. The building geometry and thermal zones are defined using coordinates; Figure 2-7 shows a sample screenshot of building geometry and zone input. Wall, roof and floor constructions are created by specifying layers of materials for each surface. Schedules and internal gains are also added to the model. The HVAC system must be modeled before a simulation is run, though HVAC templates exist to simplify this, and equipment may be autosized based on peak conditions.



Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6
User Supplied Surface Name		SURFACE NORTH	SURFACE EAST	SURFACE SOUTH	SURFACE WEST	SURFACE FLOOR	SURFACE ROOF
Surface Type		WALL	WALL	WALL	WALL	FLOOR	ROOF
Construction Name of the Surface		wall	wall	wall	wall	floor and roof	floor and roof
Zone Name		ZONE ONE	ZONE ONE	ZONE ONE	ZONE ONE	ZONE ONE	ZONE ONE
OutsideFaceEnvironment		ExteriorEnvironment	ExteriorEnvironment	ExteriorEnvironment	ExteriorEnvironment	Ground	ExteriorEnvironment
OutsideFaceEnvironment Object							
Sun Exposure		SunExposed	SunExposed	SunExposed	SunExposed	NoSun	SunExposed
Wind Exposure		WindExposed	WindExposed	WindExposed	WindExposed	NoWind	WindExposed
View Factor to Ground		0.5	0.5	0.5	0.5	0	0
Number of Surface Vertex Groups -- Num		4	4	4	4	4	4
Vertex 1 X-coordinate	m	8	8	0	0	0	0
Vertex 1 Y-coordinate	m	6	0	0	6	0	6
Vertex 1 Z-coordinate	m	2.7	2.7	2.7	2.7	0	2.7
Vertex 2 X-coordinate	m	8	8	0	0	0	0
Vertex 2 Y-coordinate	m	6	0	0	6	6	0
Vertex 2 Z-coordinate	m	0	0	0	0	0	2.7
Vertex 3 X-coordinate	m	0	8	8	0	8	8
Vertex 3 Y-coordinate	m	6	6	0	0	6	0
Vertex 3 Z-coordinate	m	0	0	0	0	0	2.7
Vertex 4 X-coordinate	m	0	8	8	0	8	8
Vertex 4 Y-coordinate	m	6	6	0	0	0	6
Vertex 4 Z-coordinate	m	2.7	2.7	2.7	2.7	0	2.7
Vertex 5 X-coordinate	m						

Figure 2-7: Sample building geometry and zone input in EnergyPlus.

Like TRNSYS, EnergyPlus has a modular structure where users may add systems modules if they wish to create a new system. Figure 2-8 shows the structure of the primary components of this program. EnergyPlus contains some accurate models not found in other programs, such as a slab and basement program to model heat transfer from the ground. The program also has a good library of models for new technologies, including heat pumps, solar air preheating, solar hot water systems, heat recovery, and demand controlled ventilation. The program has a number of HVAC templates to simplify modeling the HVAC system. Like DOE-2 and TRNSYS, EnergyPlus uses a variation of the transfer function method to account for thermal mass effects.

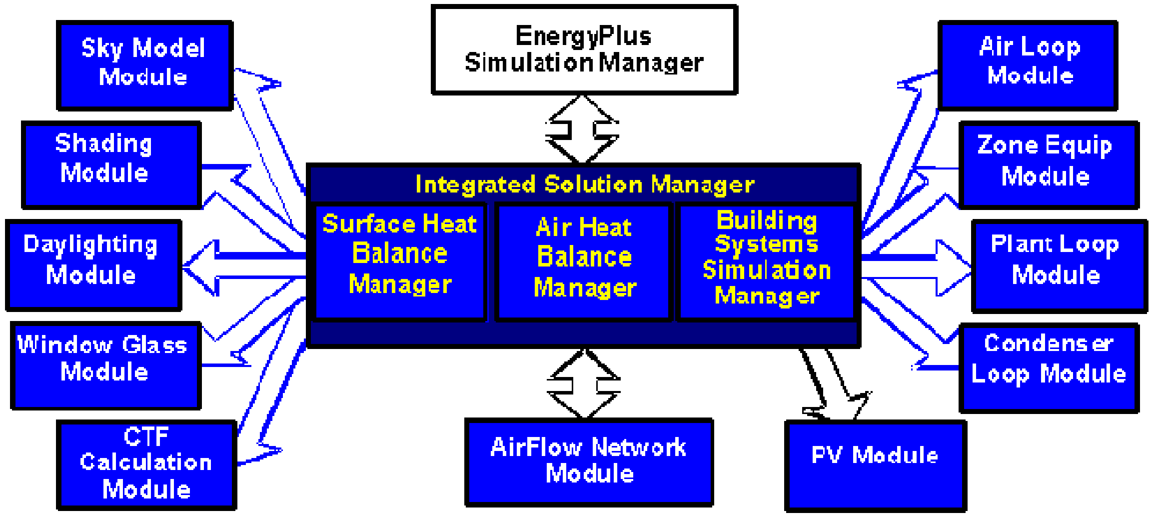


Figure 2-8: EnergyPlus program structure.

EnergyPlus has good accuracy when the building enclosure and systems are well known. However, this program does not output building loads. This program is more difficult to use than TRNSYS and DOE-2 as it lacks a graphical user interface. A number of graphical user interfaces are being developed for EnergyPlus for purchase.

2.5 ESP-r

Development of ESP-r (University of Strathclyde Energy Systems Research Unit 2002) began in the mid 1970s at the Univeristy of Strathclyde in Glasgow, Scotland. This program is free software that operates in Unix/Linux. ESP-r has a much higher learning curve than all other programs discussed thus far, however a wide range of systems can be simulated with a high degree of accuracy.

A building model is formed using command-line inputs. Each zone requires a file each for geometry, construction and operations (schedules). The geometry is entered using (x,y,z) coordinates to define corners and connections. A sample geometry zone input file is shown in Figure 2-9, and a sample construction input file in Figure 2-10. These screenshots illustrate the complexity of defining a building in ESP-r. Once the geometry, construction, and operations have been defined, files can be added to specify shading, blinds, view factors, air flow, internal gains, and convection coefficients. A plant can be added once the building model has been created. However, it is common and encouraged to omit the plant model and evaluate loads in the early design stages, when details of the plant are unclear.

```
# geometry of reception defined in: ../zones/reception.geo
GEN  reception              # type   zone name
     34      14   0.000    # vertices, surfaces, rotation angle
#   X co-ord, Y co-ord, Z co-ord
     1.00000     1.00000     0.00000  # vert  1
     9.00000     1.00000     0.00000  # vert  2
     9.00000     4.50000     0.00000  # vert  3
     9.00000     9.00000     0.00000  # vert  4
     5.00000     9.00000     0.00000  # vert  5
     5.00000     5.00000     0.00000  # vert  6
     1.00000     5.00000     0.00000  # vert  7
     1.00000     1.00000     3.00000  # vert  8
     9.00000     1.00000     3.00000  # vert  9

     9.00000     4.00000     1.00000  # vert 32
     9.00000     4.00000     2.25000  # vert 33
     9.00000     2.00000     2.25000  # vert 34
# no of vertices followed by list of associated vert
  10,  1,  2,  9,  8,  1, 15, 18, 17, 16, 15,
  10,  2,  3, 10,  9,  2, 31, 34, 33, 32, 31,
   8,  3, 19, 22, 21, 20,  4, 11, 10,
   4,  4,  5, 12, 11,
   8,  5, 23, 26, 25, 24,  6, 13, 12,
   4,  6,  7, 14, 13,
   8,  7, 27, 30, 29, 28,  1,  8, 14,
   7,  8,  9, 10, 11, 12, 13, 14,
  13,  1, 28, 27,  7,  6, 24, 23,  5,  4, 20, 19,  3,  2,
   4, 15, 16, 17, 18,
   4, 19, 20, 21, 22,
   4, 23, 24, 25, 26,
   4, 27, 28, 29, 30,
   4, 31, 32, 33, 34,
# unused indices
   0  0  0  0  0  0  0  0  0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
    3   0   0   0    # default insolation distribution
# surface attributes follow:
# id  surface      geom  loc/  mlc db       environment
# no  name         type  posn  name         other side
  1, south         OPAQ  VERT  extern_wall  EXTERIOR
  2, east          OPAQ  VERT  extern_wall  EXTERIOR
  3, pasg          OPAQ  VERT  gyp_blk_ptn  SIMILAR
  4, north         OPAQ  VERT  extern_wall  EXTERIOR
  5, part_a        OPAQ  VERT  gyp_gyp_ptn  office
  6, part_b        OPAQ  VERT  gyp_gyp_ptn  office
  7, west          OPAQ  VERT  extern_wall  EXTERIOR
  8, ceiling       OPAQ  CEIL  ceiling      roof_space
  9, floor         OPAQ  FLOR  floor_1      CONSTANT
 10, glz_s         TRAN  VERT  dbl_glz      EXTERIOR
 11, door_p        OPAQ  VERT  door         SIMILAR
 12, door_a        OPAQ  VERT  door         office
 13, door_w        OPAQ  VERT  door         EXTERIOR
 14, east_glz      TRAN  VERT  dbl_glz      EXTERIOR
```

Figure 2-9: Sample ESP-r zone geometry file.

```
# thermophysical properties of reception defined in reception.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name       | database name
    4,     1  #  1 south        extern_wall
    4,     1  #  2 east         extern_wall
    2,     0  #  3 passage      intern_wall
    4,     1  #  4 north        extern_wall
    4,     1  #  5 part_a       extern_wall
    4,     1  #  6 part_b       extern_wall
    4,     1  #  7 west         extern_wall
    4,     1  #  8 ceiling      roof_1
    4,     0  #  9 floor        floor_1
    3,     1  # 10 glz_s        d_glz
    1,     0  # 11 door_p       door
    1,     0  # 12 door_a       door
    1,     0  # 13 door_w       door
  3,   0.170,   # air gap position & resistance for surface  1
  3,   0.170,   # air gap position & resistance for surface  2
  3,   0.170,   # air gap position & resistance for surface  4
  3,   0.170,   # air gap position & resistance for surface  5
  3,   0.170,
  3,   0.170,   # air gap position & resistance for surface  6
  3,   0.170,   # air gap position & resistance for surface  7
  3,   0.170,   # air gap position & resistance for surface  8
  2,   0.170,   # air gap position & resistance for surface 10
# conduc-  |  density | specific | thick- | surf|layer
# tivity   |          | heat     | ness(m)|     |
    0.9600,    2000.0,     650.0,  0.1000  #  1  1
    0.0400,     250.0,     840.0,  0.0750  #     2
    0.0000,       0.0,       0.0,  0.0500  #     3
    0.4400,    1500.0,     650.0,  0.1000  #     4
    0.9600,    2000.0,     650.0,  0.1000  #  2  1
    0.0400,     250.0,     840.0,  0.0750  #     2
    0.0000,       0.0,       0.0,  0.0500  #     3
    0.4400,    1500.0,     650.0,  0.1000  #     4
```

Figure 2-10: Sample ESP-r zone construction file.

Similar to TRNSYS, users can select from a library of modules to add systems to their particular building simulation. If a module for the desired system does not exist users can create a new module, though this is difficult and only recommended for advanced users.

ESP-r uses the heat balance method to calculate building energy loads. The program defines each energy flow path in the building by a corresponding set of equations, which are then solved simultaneously using numerical methods. As discussed previously, this is the most computationally intensive method of calculating loads but also the most accurate method.

ESP-r is commonly used for research due to its wide modeling capabilities and high degree of accuracy. ESP-r is not popular in industry due to the high learning curve. One of the major benefits of ESP-r is that it allows and encourages users to separate loads from systems by modeling the building without a plant. Another major benefit is that, like TRNSYS, it may be used to model new systems, though only by advanced users.

2.6 SUNREL

SUNREL (Deru 2002) was developed by the National Renewable Energy Laboratory (NREL) to model loads on small buildings. The current version of this program only calculates loads, it does not model energy consumption of HVAC systems. This program calculates hourly energy loads for a year using the thermal network model. One of the primary strengths of SUNREL is its high accuracy in modeling solar radiation effects, including solar heat gain through walls and windows and systems such as Trombe walls.

SUNREL is fairly easy to use, though it does require command-line input (unless a graphical user interface is purchased) as the inputs are simple and clear. The program is based around thermal zones defined as a series of nodes. Users first define thermal zones and heat flow paths between zones, such as walls, internal gains, solar radiation, and infiltration. Figure 2-11 illustrates a single zone thermal network that may be defined in SUNREL, where heat transfer acting on a space occurs through four walls and infiltration. Exterior surfaces (size and orientation) and construction (walls, windows, roof, etc.) are defined via command-line inputs. Figure 2-12 shows a sample command-line input for an insulated stud wall. Though the input is entered in code, the code is simple and easy to understand.

SUNREL is easy to use, free, accurate, and outputs building loads. The major drawback of this program is that it currently does not model systems energy.

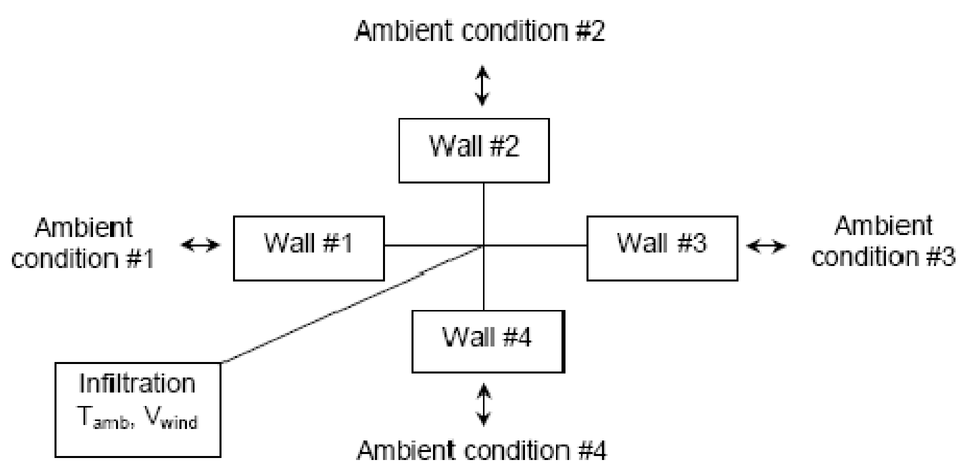


Figure 2-11: Sample SUNREL single zone thermal network (Deru 2002).

```
&WALLS
walltype   =  'stud'   'cavity'
wfrntzone  =  'house'  'house'
wbackzone  =  'south'  'south'
wallhgt    =  2.5   2.5
wallong    =  10.0  10.0
wallpercent =    15.0  85.0
```

Figure 2-12: Sample SUNREL input for an insulated stud wall (Deru 2002).

2.7 HOT2000

HOT2000 (Natural Resources Canada 2008) was developed by Natural Resources Canada to model energy consumption of houses. Figure 2-13 shows a screenshot of an input page from HOT2000. HOT2000 uses the bin method of estimating annual energy consumption. This program takes user inputs about a house organized through a hierarchical tree structure, similar to the EE4 program. This program is very easy to use but has limited accuracy since it uses the bin method, as discussed previously. HOT2000 is presented here to show an example of a bin-method program but is not used for commercial building energy simulation.

The bin method was used in HOT2000 because of the high cost of computer speed and storage at the time of its development. Now that speed and storage are non-factors, an updated program called HOT3000 is currently under development. This updated version is still intended for modeling residential energy consumption but will use ESP-r as an engine.

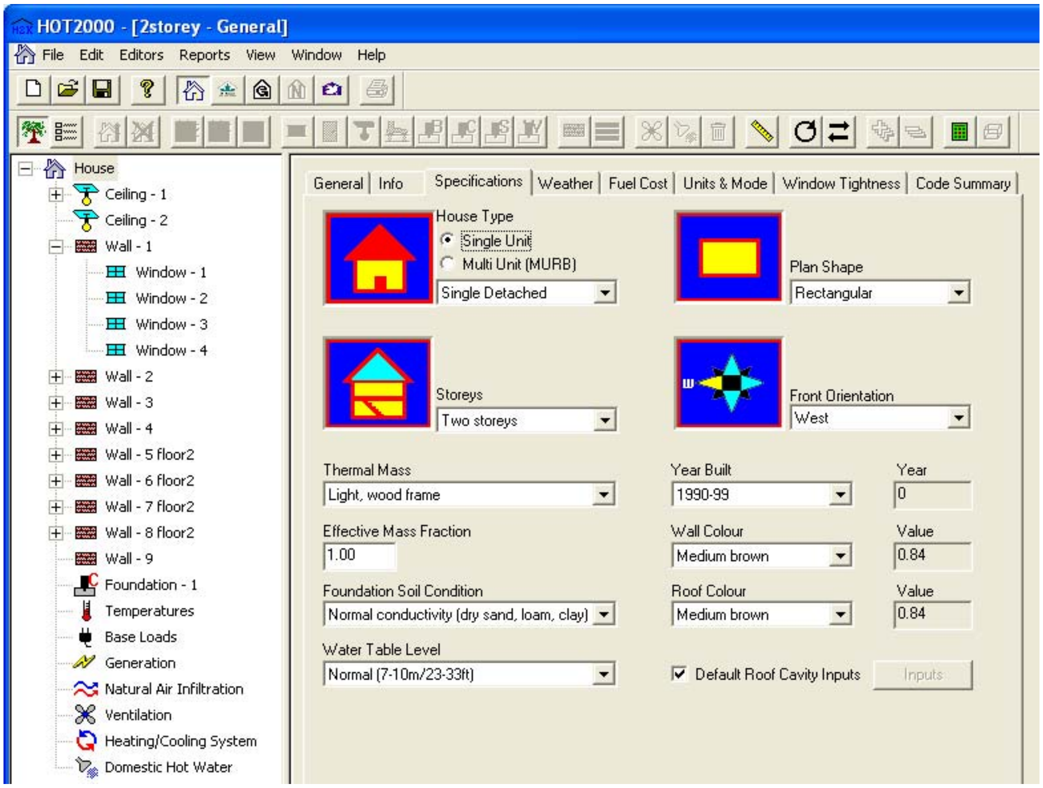


Figure 2-13: Sample HOT2000 input page.

2.8 Summary

While hundreds of energy modeling programs exist, a select few are widely used in the current energy modeling industry. Each program has different strengths and weaknesses, varying levels of accuracy and ease of use. Table 2-1 shows a summary of the strengths and weaknesses of the programs reviewed in this section.

A number of desirable features can be identified from the programs reviewed. Programs should be easy to use and should not require significant learning time. Programs should be adaptable; users should be able to add or modify systems to reflect their building design. Programs should facilitate simulation in early design stages when not all system details are known, and provide feedback on loads.

The program to be developed in this thesis aims to address some of the drawbacks of existing energy modeling programs. The proposed program will be spreadsheet-based. A spreadsheet program will be easy to use for both mechanical engineers and architects. A spreadsheet-based program can be modular and allow users to add or modify systems without having to learn programming code. The program will allow users, particularly architects, to view how design decisions affect energy performance early in the design stages by calculating loads and systems energy separately and providing clear, useful feedback to users on both loads and systems energy. This program will attempt to build off the easy to use characteristics of DOE-2, eQuest, SUNREL and HOT2000, as well as the modularity of TRNSYS, EnergyPlus and ESP-r.

Table 2-1: Summary of modeling programs reviewed.

Program	Strengths	Weaknesses	Comments
DOE-2	Easy to use with graphical user interfaces (eQuest, EE4) Free	Calculations are out of date, lacks good engineering documentation Cannot model newer systems	Acceptable for most industry modeling needs
TRNSYS	Easy to use interface Modular structure allows addition of new systems	Expensive to purchase Requires detailed knowledge of building Creation of new modules requires programming skills	Useful for research applications and industry cases where a new or innovative system model is required
EnergyPlus	Modular structure allows addition of new systems Free	Difficult to use without graphical interface Cannot separate loads and systems energy Requires detailed knowledge of building parameters Creation of new modules requires programming skills	Useful for research applications and industry cases where a new or innovative system model is required
ESP-r	Modular structure allows addition of new systems Accurate calculation methods Free	Difficult to use, high learning curve Requires detailed knowledge of building parameters Creation of new modules requires programming skills	Useful for research applications where high degree of accuracy is required
SUNREL	Models building loads Easy to use	Does not model HVAC systems	Useful for modeling loads only
HOT2000	Easy to use	Limited to low-rise residential buildings Less accurate calculation method	Good for common residential applications

There are some limitations to using a spreadsheet for annual energy modeling. Computation time and capacity may become an issue as more complex systems are modeled, since the program must perform calculations for each hour in a year. The program will be created for a single thermal zone; multiple zones will be more difficult to implement and may require separate spreadsheet files.

Chapter 3
Loads Model

3.1 Model Structure

Figure 3-1 shows the general structure of the BELA program. The program takes inputs that describe the building and calculates the building energy consumption on an hourly basis. An overview of the program is provided in this section, and more detailed descriptions are provided in the sections that follow.

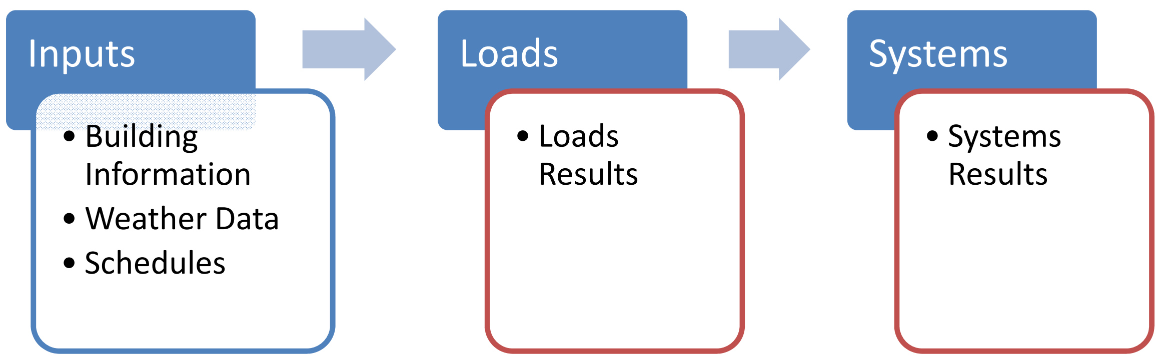


Figure 3-1: Model structure.

BELA has three input sheets: Building Information, Weather Data and Schedules. The Building Information requires the user to input such details as dimensions, window to wall ratio, enclosure insulation values, and so on. The weather data tab takes hourly weather data for a year pasted from a standard weather file such as Canadian Weather for Energy Calculations (CWEC) or Typical Meteorological Year (TMY), which are available free of charge from government bodies (Environment Canada, US Department of Energy). Schedules control when the building is consuming energy and can be adjusted by the user.

BELA uses building inputs to calculate loads on the building and also calculates the total system energy. It is important to distinguish between load energy and system energy. Loads are the required heating and cooling demand, or lighting and equipment energy. For example, heat loss due to conduction that occurs through an exterior wall causes an instantaneous load in kilowatts. The total heating or cooling load is the sum of all sources of heat transfer acting on the building. Systems energy is the actual building energy consumption, in other words, the energy that passes through a meter. Systems energy incorporates the efficiency of meeting the loads on the building. For example, on a winter day with a net heating load, the system energy is the total energy consumed by the boiler, pumps and fans to create and distribute heat to the space to maintain a constant indoor temperature. The program calculates load and system energy separately, and displays the results for each separately. The loads portion of the program will be presented later in this chapter.

3.2 Description of Loads Model

3.2.1 Building Inputs

A complex building can be reduced to a simple box for the purpose of energy modeling, often with little loss in accuracy. Complexities may be in the form of non-rectangular shapes, multiple enclosure assemblies, different types of windows, multiple zones, and so forth. The program in its current form makes a number of simplifications that could be expanded upon in future versions. These simplifications and loss in accuracy are discussed with the building inputs in the sections that follow. The required building inputs include:

- Dimensions
- Window to Wall Ratio
- Enclosure Thermal Resistance
- Window Thermal Conductance
- Window Solar Heat Gain Coefficients (SHGC)
- Infiltration Rate
- Roof and Wall Solar Absorptance
- Occupant Density
- Lighting and Plug Load Density
- Indoor Temperature Setpoints

3.2.1.1 Dimensions

The dimensions of the building in the North-South and East-West directions are entered as inputs. For non-rectangular shapes, the perimeter, roof area and floor area should be entered exactly; the only inaccuracy created by this is the effect of shading. The number of stories and floor-to-floor height are also specified. BELA currently only models buildings facing due north. However buildings tilted off due north could be easily implemented by adjusting the solar radiation algorithm.

3.2.1.2 Window to Wall Ratio

The window to wall ratio (WWR) is the total window area (including frame area) divided by the total elevation wall area (glazed and opaque). The WWR is specified for each elevation (N, S, E and W).

3.2.1.3 Enclosure Thermal Resistance

The thermal resistance or R-value must be input for the exterior wall, roof, foundation, and doors. It is critical that the true overall R-value of the assembly be entered, including thermal bridges and surface films. For buildings with multiple assembly types, area-weighting can be used to calculate a single overall R-value. For example, for a building with three different wall assemblies with R-values R_1, R_2 and R_3 and exterior surface areas A_1, A_2, and A_3, the equivalent R-value would be,

$$R = \frac{R_1A_1 + R_2A_2 + R_3A_3}{A_1 + A_2 + A_3}$$

An algorithm could be added to subsequent versions to perform this calculation automatically.

3.2.1.4 Window Thermal Conductance

An overall thermal conductance or U-value must be input for all exterior windows. The U-value of a window varies at different locations of the window: center of glass, edge of glass and frame. The U-value entered into this spreadsheet is the total product U-value, which can be calculated using area-weighting of the center of glass, edge of glass and frame. The edge-of-glass is defined as the area within 63.5 mm (2.5 inches) of the window frame. As with other enclosure components, if multiple types of windows exist area-weighting can be used to calculate a single average product U-value for all of the glazing on the building.

3.2.1.5 Window Solar Heat Gain

The solar heat gain coefficient is the fraction of solar radiation that results in heat gain to the space. The window solar heat gain coefficient (SHGC) is entered for windows at each elevation since it may be beneficial to specify different SHGC's at different elevations. As with conductance, the SHGC entered should be the overall product SHGC, which can be calculated from the frame and glazing SHGC using area weighting.

It is important to note that SHGC is different from Shading Coefficient (SC), which is used by some modeling programs including DOE-2. SC was phased many years ago as it is based on comparison to a single sheet of glass (NFRC 2003).

The current model does not include exterior or interior window shades however an algorithm to simulate shading could be easily added.

3.2.1.6 Roof and Wall Solar Absorptance

The solar absorptance is the fraction of incident solar radiation absorbed by the roof or wall. Solar absorptances for common building materials are listed in Table 3-1 (McQuiston 2005). This information is important as it influences how hot exterior surfaces become when exposed to the sun.

Table 3-1: Solar absorptances (McQuiston 2005).

Surface	Absorptance
Brick, red	0.63
Paint, black	0.94
Paint, white	0.26
Sheet metal, galvanized, new	0.65
Sheet metal, galvanized, weathered	0.80
Shingles, gray	0.82
Shingles, brown	0.91
Shingles, black	0.97
Shingles, white	0.75
Concrete	0.60 – 0.83
Asphalt	0.90 – 0.95
Grass	0.80 – 0.84
Snow, fresh	0.10 – 0.25
Snow, old	0.30 – 0.55

3.2.1.7 Infiltration Rate

Infiltration is air leakage through cracks and unplanned penetrations in the building enclosure. In this model a single infiltration rate is entered in l/s per m^2 of enclosure wall area. The infiltration rate entered into the program should be at natural pressures. ASHRAE guidelines on infiltration rates are normally given at a test pressure, typically either 50 Pa or 75 Pa. When these guidelines are used, the infiltration rate must first be converted to the rate at natural pressures. This can be done using the relation,

$$\boldsymbol{Service\ Leakage = Test\ Leakage} \times \left(\frac{\boldsymbol{Service\ Pressure}}{\boldsymbol{Test\ Pressure}}\right)^{\mathbf{0.65}} \quad \text{Eq. 3-1}$$

In reality, infiltration rate varies with wind speed and outdoor temperature; a more accurate algorithm could be implemented to calculate an infiltration rate based on these values. However, buildings are now designed and constructed to be more air tight than in the past. As such, the infiltration rate does not have as great of an effect on overall energy performance, and so the lack of precision in infiltration rate should not have a significant impact on the model. An infiltration schedule could also be implemented to simulate doors opening more frequently at certain times of the day, or open windows at certain times of the year.

3.2.1.8 Occupant Density

The total occupant density for the building is entered in people per m^2 of floor area. The occupant density will vary throughout the different spaces in a building. For example, meeting rooms will have a high occupant density while private offices will have a low occupant density. A calculation could be added to the model to list all space types and the floor area and occupant density of each space type, and then calculate the area-weighted average occupant density for the entire building.

3.2.1.9 Lighting and Plug Load Density

The average lighting and plug load densities for the building are entered in W/m^2 floor area. Plug loads include equipment such as computers, photocopy machines, and so on. Task lighting is currently not included in the model but could be easily added. As with occupant density, an area-weighted average could be added to account for varying lighting and plug load densities throughout the building.

3.2.1.10 Indoor Temperature

The winter and summer indoor temperature set points are entered in degrees Celsius. The program applies a sine wave to these values to vary the indoor temperature set point over the course of a year. The winter low occurs in January and the summer high occurs in July, with values in between scaled along a sine wave. The indoor temperature on a given day is,

$$\boldsymbol{T = T_w + (T_s - T_w)\sin\left[\frac{90(n-1)}{182}\right]} \qquad \text{Eq. 3-2}$$

Where T_w = Winter (low) set point, C

T_s = Summer (high) set point, C

n = day of year

A different method of entering indoor temperature such as daily or annual temperature schedules and nighttime setback could be easily added.

3.2.1.11 Indoor Humidity

Indoor humidity is not a user input, but it is calculated at each hour before the loads calculations are performed. Indoor humidity changes with the amount of moisture added to or removed from the building. Moisture is added and removed by three modes: people (moisture addition only), infiltration and ventilation. The change in moisture content in kg per hour is,

$$\boldsymbol{M = M_{people} + M_{infiltration} + M_{ventilation}} \qquad \text{Eq. 3-3}$$

Moisture generated by people within the building depends on the occupants' activity level. Table 3-2 shows typical moisture production rates for various activity levels (Harriman 2001).

Table 3-2: Moisture production rates (Harriman 2001).

Activity	Typical of	Moisture production per person {kg/h}
Seated, at rest	Theater patron	0.05
Seated, very light work	Hotel or restaurant patron	0.07
Seated, moderately active	Offices, retail cashier	0.09
Standing, light work, walking	Offices, retail patron	0.09
Walking, standing	Offices, retail floor clerk	0.11
Seated, light work	Electronic assemblers	0.2
Moderate dancing	Dancing, nursing care	0.24
Walking briskly with loads	Restaurant servers	0.27
Light exercise	Bowling, slow treadmill	0.38
Heavy work with lifting	Factory, health club machines	0.42
Athletics	Basketball, heavy exercise	0.47

Moisture change due to infiltration is calculated from the infiltration rate and the difference in indoor and outdoor air moisture content,

$$\boldsymbol{M_{inf} = A\dot{q}_{inf}\rho(W_{out} - W_{in})/1000} \qquad \text{Eq. 3-4}$$

Where M_{inf} = Moisture gained (positive) or lost (negative) through infiltration, kg/s

A = Floor area, m^2

$\dot{q}_{inf}$ = Infiltration rate per m^2 floor area, l/s-m^2

ρ = Outdoor air density, kg/m^3

W = Absolute humidity, kgv/kga

Moisture change due to ventilation is calculated from the ventilation rate and the difference in indoor and outdoor air moisture content,

$$\boldsymbol{M_{vent} = (1 - \eta_{ERV})\dot{q}_{vent}\rho(W_{out} - W_{in})/1000} \qquad \text{Eq. 3-5}$$

Where M_{vent} = Moisture gained (positive) or lost (negative) through ventilation, kg/s

η_{ERV} = Energy recover efficiency, %

$\dot{q}_{vent}$ = Ventilation rate, l/s

ρ = Indoor air density, kg/m^3

W = Absolute humidity, kgv/kga

When calculating moisture addition as above, the indoor absolute humidity (W) from the previous hour is used. The absolute humidity for the current hour is calculated by adding the moisture gained in that hour to the absolute humidity from the previous hour,

$$\boldsymbol{W_i = W_{i-1} + \frac{M_{people}+M_{inf}+M_{vent}}{\rho V}} \qquad \text{Eq. 3-6}$$

Where W_i = Absolute humidity at hour i, kgv/kga

W_{i-1} = Absolute humidity at previous hour, kgv/kga

ρ = Indoor air density, kg/m^3

V = Building volume, m^3

The partial water vapour pressure and relative humidity are calculated from the absolute humidity (Straube 2005),

$$\boldsymbol{P_w = \frac{WP_{atm}}{0.622+W}} \qquad \text{Eq. 3-7}$$

Where P_w = Partial water vapour pressure, Pa

P_{atm} = Atmospheric pressure, Pa

W = Absolute humidity, kgv/kga

$$\boldsymbol{RH = \frac{P_w}{P_{w,s}}} \qquad \text{Eq. 3-8}$$

Where RH = Relative humidity, %

$P_{w,s}$ = Saturation vapour pressure, Pa

The calculated RH can be unrealistically low or high since building components have a moisture storage capacity. The enclosure, interior finishes and furnishings all store and release moisture. This means the indoor RH will not get too high (moisture would be absorbed) or too low (moisture would be released). Programs such as WUFI model transient hygrothermal effects, however a detailed hygrothermal model is beyond the scope of this project. A more accurate hygrothermal model could be implemented for later versions of this program. The interior relative humidity has a modest impact on the cooling energy and little to no impact on heating energy. The model does not include the energy required to humidify, if any.

3.2.2 Weather Data

As with most energy modeling programs, this model uses hourly weather data for one year. A number of files with this information exist; two such data sets are Canadian Weather for Energy Calculations (CWEC), and Typical Meteorological Year (TMY). One difference in these file types is the method of determining a single year of typical weather. The more important difference for the purpose of this program is in which metrics are displayed; for example, outdoor humidity may be given as wet blub temperature, dew point, relative humidity or absolute humidity.

The metrics currently used by this program are based on the CWEC data format but could be easily altered based on other data formats. These metrics include dry bulb temperature (degrees Celsius), dew point temperature (degrees Celsius), relative humidity (%), atmospheric pressure (Pa), global horizontal radiation (W/m^2), wind speed (m/s), wind direction (degrees), and ground temperature (degrees Celsius).

Global horizontal radiation from the weather file is projected onto vertical surfaces facing north, south, east and west to determine the radiation that falls on each elevation. This is accomplished using an excel function developed by Nicholas Bronsema (Bronsema 2009). The function takes in one year of hourly global horizontal radiation data (in W/m^2) and outputs the radiation falling on horizontal surfaces facing north, south, east and west. A ground reflectance of 0.2 is assumed for the entire year.

Outdoor air properties are calculated using psychrometrics. The vapour pressure and air density are calculated from the given weather data, then used to find the absolute humidity.

The saturation vapour pressure is, (Straube 2005)

$$\boldsymbol{P_{w,s} = 1000e^{\left(52.58-\frac{6790.5}{T}-5.028\ln T\right)}} \qquad \text{Eq. 3-9}$$

Where $P_{w,s}$ = Saturation vapour pressure, Pa

T = outdoor temperature, K

The partial water vapour pressure is, (Straube 2005)

$$P_w = 133e^{18.689-\frac{4030}{T_d+235}} \quad \text{Eq. 3-10}$$

Where P_w = Partial water vapour pressure, Pa

T_d = Dew point temperature, C

Using the ideal gas law the air density is, (Straube 2005)

$$\rho = \rho_a + \rho_v = \frac{P_{atm}-P_w}{R_aT} + \frac{P_w}{R_wT} \quad \text{Eq. 3-11}$$

Where ρ = Total air density, kg/m^3

ρ_a = Density of dry air, kg/m^3

ρ_v = Density of water vapour, kg/m^3

P_{atm} = Atmospheric pressure, Pa

P_w = Partial water vapour pressure, Pa

R_a = Specific gas constant for air, J/kg-K

R_w = Specific gas constant for water, J/kg-K

Finally, the absolute humidity (in kgv/kga) is, (Straube 2005)

$$W = \frac{0.622P_w}{P_{atm}-P_w} \quad \text{Eq. 3-12}$$

These values are used later in the loads calculations.

3.2.3 Schedules

The model uses daily and weekly schedules to account for variations in building use. The model does not currently have annual schedules, though this could be easily implemented. Schedules have currently been implemented for lighting, plug loads and occupancy. Schedules could also be created for heating and cooling temperature set points and infiltration. Table 3-3 and Table 3-4 show typical daily and weekly schedule input tables for an office building, respectively.

Table 3-3: Sample daily schedule input table.

Hour	Lighting %	Plug Loads %	Occupancy %
1:00	10%	10%	0%
2:00	10%	10%	0%
3:00	10%	10%	0%
4:00	10%	10%	0%
5:00	10%	10%	0%
6:00	10%	10%	0%
7:00	55%	10%	0%
8:00	100%	100%	100%
9:00	100%	100%	100%
10:00	100%	100%	100%
11:00	100%	100%	100%
12:00	100%	100%	100%
13:00	100%	100%	100%
14:00	100%	100%	100%
15:00	100%	100%	100%
16:00	100%	100%	100%
17:00	55%	10%	10%
18:00	10%	10%	0%
19:00	10%	10%	0%
20:00	10%	10%	0%
21:00	10%	10%	0%
22:00	10%	10%	0%
23:00	10%	10%	0%
0:00	10%	10%	0%

Table 3-4: Sample weekly schedule input table.

Day	Lighting %	Plug Loads %	Occupancy %
1	100%	100%	100%
2	100%	100%	100%
3	100%	100%	100%
4	100%	100%	100%
5	100%	100%	100%
6	0%	0%	0%
7	0%	0%	0%

3.2.4 Loads Calculations

The space heating and cooling loads are calculated at each hour for a year. The following heat transfer mechanisms contribute to the space heating and cooling load,

- Conduction through the walls, windows, doors and roof
- Conduction through the foundation
- Solar heat gain through windows
- Infiltration
- Heat gain from occupants, lights and plug loads

In addition to space heating and cooling loads, the electrical lighting and plug loads are totaled. Domestic hot water (DHW) loads are currently not calculated but could be easily added to the model. It is important to note that this model assumes no plenums are present. A plenum is space between the drop down ceiling and the floor above a space. This space may be used for air circulation as part of the HVAC system. Plenums have a negligible effect on total building energy performance. In the past, the most significant effect of plenums on total building energy consumption was due to inefficient light bulbs heating up return air in plenums, which improved the efficiency of air conditioning equipment. Now that lights produce less heat, this increase in cooling equipment performance is negligible. Plenums may still be important in determining required amounts of airflow to a particular space, however when calculating the total building energy consumption the effect of plenums is relatively small.

3.2.4.1 Conduction

Conduction through the walls, windows, doors and roof is determined by first calculating the surface temperature. Surface temperature is calculated using an energy balance where energy transfer to the inside and outside is equal to absorbed solar radiation,

$$\mathbf{I_s \alpha - (T_s - T_{out}) h_c - (T_s - T_{in}) U = 0} \qquad \text{Eq. 3-13}$$

Where I_s = Solar radiation on surface, W/m2

α = Solar absorbtance

T_s = Surface temperature, °C

T_{out} = outdoor air temperature, °C

T_{in} = indoor air temperature, °C

h_c = surface film coefficient, W/m^2-°C

U = overall heat transfer coefficient (U-value) of the wall or roof assembly, W/m^2-°C

Solving for T_s gives,

$$\boldsymbol{T_s = \frac{I_s\alpha + T_{out}h_c + T_{in}U}{h_c + U}} \quad \text{Eq. 3-14}$$

The surface temperature is calculated for each wall elevation and the roof. The heat transfer by conduction, Q_{cond}, through each surface with area A is (ASHRAE 2009),

$$\boldsymbol{Q_{cond} = UA(T_s - T_{in})} \qquad \text{Eq. 3-15}$$

The value of the surface film coefficient, h_c, is difficult to determine as it depends on wind speed and surface roughness. A number of relations for h_c are provided in ASHRAE Fundamentals (2009). The average surface film coefficient for exterior surfaces is about 17 W/m^2-K (Straube 2005). DOE-2 calculates h_c using the following equation (LBL 1982),

$$\boldsymbol{h_c = A + (B \times V) + (C \times V^2)} \qquad \text{Eq. 3-16}$$

Where h_c = Surface film coefficient, W/m^2-°C

V = wind speed, m/s

A, B, C = Coefficients listed in Table 3-5

Table 3-5: DOE-2 coefficients for surface film calculation (LBL 1982).

Surface Roughness	A	B	C
Stucco	11.58	6.796	0
Brick and rough plaster	12.49	4.687	0.0378
Concrete	10.79	4.827	0
Clear pine	8.23	4.611	-0.0755
Smooth plaster	10.22	3.569	0
Glass, white paint on pine	8.23	3.836	-0.0472

A brick wall with a low wind speed of 2 m/s, this equation gives h_c = 22 W/m^2-°C, while a moderate wind speed of 5 m/s gives h_c = 37 W/m^2-°C. The values of h_c seem to be unreasonably high, certainly higher than the average 17 W/m^2-°C.

The programs TRNSYS and ESP-r allow users to either manually enter values for h_c, or automatically calculate values using various relations found in literature. In this program, the average h_c = 17 W/m^2-°C was used independent of wind speed. A better model of surface film coefficient should be investigated for future versions, possibly using the relations from TRNSYS and ESP-r.

Calculation of conductive heat transfer through the foundation requires knowledge of the ground temperature. The average monthly ground temperature at a depth of 0.5 m is provided in the CWEC file. However, ground temperatures below a building experience less temperature variation; this makes it difficult to determine an accurate calculation of foundation conduction. To account for thermal storage at lower depths, the ground temperature in this model is damped by an arbitrary factor of 0.65 about the mean. Conduction through the foundation is then calculated (ASHRAE 2009),

$$\boldsymbol{Q_{cond} = UA\left(T_g - T_{in}\right)} \quad \text{Eq. 3-17}$$

Where U = heat transfer coefficient (U-value) of the foundation assembly, W/m^2-°C

A = foundation area, m^2

T_g = ground surface temperature, °C

The ground conduction calculation should be investigated further for future versions of the model.

3.2.4.2 Solar Heat Gain

Solar radiation on a horizontal surface from the CWEC weather file is projected onto vertical north, south, east and west surfaces to determine the solar radiation falling on windows at each elevation. The solar heat gain is then calculated by summing the solar heat gain at each elevation (ASHRAE 2009),

$$\boldsymbol{Q_{SHG} = \sum q_i A_i SHGC_i} \quad \text{Eq. 3-18}$$

Where q_i = Solar radiation hitting elevation i, W/m^2

A_i = Window area at elevation i, m^2

$SHGC_i$ = Solar heat gain coefficient of windows at elevation i

i = {North, South, East, West}

3.2.4.3 Air Infiltration

Air infiltration creates a sensible load and a latent load. The air infiltration rate is a user input, in l/s per m^2 floor area. The sensible infiltration load is (ASHRAE 2009),

$$\boldsymbol{Q_{inf,s} = \dot{q} A \rho c_p (T_{out} - T_{in})} \quad \text{Eq. 3-19}$$

Where $\dot{q}$ = Air leakage rate, l/s per m^2 wall area

A = Floor area, m^2

ρ = Indoor air density, kg/m^3

c_p = Specific heat capacity of air, J/kg-K

The latent infiltration load is only calculated when greater than zero (that is, when dehumidification is required). Therefore, it is assumed that no humidification is needed or used since many buildings do not have humidification systems. The total latent load is (McQuiston 2005; Straube 2005),

$$\boldsymbol{Q_{inf,l} = \dot{q}A(W_{out} - W_{in})(2501 + 1.805T_{in})} \quad \text{Eq. 3-20}$$

Humidification could be added to the model if desired.

3.2.4.4 Internal Heat Gains

Heat gain from occupants is the occupant density (people/m^2) times heat gain per person (W/person) times the floor area (m^2). Occupants create both a sensible heat load and a latent heat load. The sensible and latent heat gains per person are entered separately. Heat gain due to lights and plug loads is the lighting or plug load density input by the user (W/m^2) times the floor area (m^2).

3.2.5 Thermal Mass

The heating or cooling load at any particular time differs from the instantaneous gains and losses calculated previously due to heat absorbed by thermal mass and released at later times. There are various methods of accounting for this effect; discussion of the various methods can be found in ASHRAE Fundamentals Chapter 19 (ASHRAE 2009) and in this paper (Section 2.1).

The weighting factor method was selected for this program for its simplicity. This method applies weighting factors to each instantaneous (hourly) gain. The weighting factors are transfer functions that relate heating or cooling load to instantaneous gain. This method is explained in greater detail by Stephenson and Mitalas (1967) and Mitalas (1972). The weighting factor model is simple to apply but not as accurate as other methods; a better model such as the Radiant Time Series method should be implemented for future versions of this program.

Weighting factors differ for each heat transfer source and vary with the amount of thermal mass in the building. Weighting factors have been calculated for a number of scenarios; McQuiston and Spitler (1992) provide tables with weighting factors for a number of configurations. In DOE-2 based programs, weighting factors are automatically generated based on user inputs about the building (mainly the amount of thermal mass). Table 3-6 and Table 3-7 show weighting factors that were generated by eQuest for a thermally lightweight and thermally massive building, respectively. In this program, the user must manually input weighting factors. A better algorithm could be developed to have the program choose from a list of pre-defined weighting factors based on the user's input of the building thermal mass.

Table 3-6: eQuest weighting factors for thermally lightweight construction.

	V_0	V_1	W_1
Conduction	0.94386	0.05354	0.0026
Solar Heat Gain	0.85703	0.14037	0.0026
People & Equipment	0.94386	0.05354	0.0026
General Lighting	0.91567	0.08173	0.0026
Task Lighting	0.91027	0.08713	0.0026

Table 3-7: eQuest weighting factors for thermally massive construction.

	V_0	V_1	V_2	W_1	W_2
Conduction	0.63352	-0.76520	0.16675	1.26391	-0.30311
Solar Heat Gain	0.30443	-0.40111	0.10411	1.51970	-0.52895
People & Equipment	0.58050	-0.69305	0.14702	1.26391	-0.30311
General Lighting	0.59848	-0.71752	0.15371	1.26391	-0.30311
Task Lighting	0.59848	-0.71752	0.15371	1.26391	-0.30311

The weighting factors are used with the current and past instantaneous gains/losses and the past weighted load as follows (ASHRAE 2009),

$$\boldsymbol{Q_\theta = V_0 q_\theta + V_1 q_{\theta-1} - W_1 Q_{\theta-1}} \qquad \text{Eq. 3-21}$$

Where Q_θ = Heating or cooling load at hour θ

$Q_{\theta-1}$ = Heating or cooling load at hour θ – 1

q_θ = Instantaneous heat gains or losses at hour θ

$q_{\theta-1}$ = Instantaneous heat gains or losses at hour θ – 1

V_0, V_1, W_1 = Weighting factors

Weighting factors are applied to heat transfer that occurs by conduction, solar heat gain, people, equipment and lighting. Weighting factors are not applied to heat transfer due to infiltration since this is assumed to be an instantaneous load not affected by thermal mass.

3.3 Loads Model Comparison to eQuest

Output from the loads model was compared to loads calculated by eQuest in order to validate the loads model output and to better understand the assumptions made by eQuest. eQuest was chosen for this exercise since it is one of the most widely used energy modeling programs in industry, and uses the same method of accounting for thermal mass as this model.

3.3.1 Sample Building Model

Identical buildings were entered into the energy model and eQuest. A number of simplifications had to be made in the eQuest model since the spreadsheet is not as detailed as eQuest at this time. Schedules were simplified in eQuest to match the spreadsheet; heating and cooling set points were set to a single value at all hours, and infiltration was set to be constant for all hours. Holidays and daylight savings time were turned off in the eQuest model.

eQuest gives the option of defining an enclosure by listing the layers in the enclosure or by entering a single overall U-value. If the first method is chosen, eQuest calculates the overall U-value using material properties from its library. For this model, enclosure constructions were entered by specifying the U-value rather than entering layers so that the same U-values could be used in the spreadsheet without uncertainty as to how the U-value is calculated. The building shell was set to thermally lightweight construction and the weighting factors generated by eQuest were used in the spreadsheet (shown in Table 3-6). Table 3-8 shows inputs to both eQuest and the spreadsheet model.

Table 3-8: Comparison model inputs.

General	
Location	Toronto, ON
Number of Stories	2
Length, N-S	63 m
Length, E-W	40 m
Floor to Floor Height	3.7 m
Indoor Temperature	24°C
Enclosure	
Wall R-Value	4.4 m^2-K/W (25 hr-ft^2-F/Btu)
Wall Solar Absorptance	0.8
Roof R-Value	7.0 m^2-K/W (40 hr-ft^2-F/Btu)
Roof Solar Absorptance	0.8
Foundation R-Value	1.8 m^2-K/W (10 hr-ft^2-F/Btu)
Total Window U-Value	1.97 W/m^2-K (0.347 Btu/hr-ft^2-F)
Window Solar Heat Gain Coefficient	0.38
Window to Wall Ratio	28%
Doors	5 doors, 2.1 m x 1.8 m (7 ft x 6 ft)
Infiltration Rate	0.5 l/s-m^2 floor (0.1 cfm/ft^2)
Internal Gains	
Occupants – Sensible	73 W/person
Occupants – Latent	62 W/person
Occupant Density	7 people per 100 m^2
Lights	8.3 W/m^2
Plug Loads	12.5 W/m^2

3.3.2 Comparison of eQuest and Loads Model

The monthly energy load from each load source in the spreadsheet and eQuest models were compared. Results were generally good but sometimes varied significantly. Results are discussed separately for each category.

3.3.2.1 Wall Conduction

Table 3-9 shows the wall conduction loads calculated by the two models. The percent difference in wall conduction results is low in winter and swing months but high in summer months. However, the absolute difference is only significantly higher in the month of August. Conduction is lower in the summer months which creates a larger percent difference even though absolute difference is fairly consistent. A negative percent difference means the eQuest value was larger than the spreadsheet value.

Table 3-9: Wall conduction comparison results.

	Spreadsheet (kWh)	eQuest (kWh)	% Difference	Absolute Difference (kWh)
January	-7385	-7080	-4%	305
February	-6540	-6306	-4%	235
March	-5829	-5591	-4%	238
April	-3925	-3705	-6%	220
May	-2296	-2050	-12%	246
June	-727	-476	-53%	251
July	55	342	-84%	287
August	-238	229	-204%	467
September	-1560	-1203	-30%	357
October	-3554	-3326	-7%	228
November	-4968	-4728	-5%	240
December	-6685	-6559	-2%	126
Total	-43652	-40452	-8%	3200

It is unknown how eQuest calculates the exterior surface film coefficient. The spreadsheet model uses an average value of 17 W/m^2-K, though in reality the surface film coefficient varies with wind speed, solar radiation and surface roughness (Straube and Burnett 2005). Further, the equation used by DOE-2 to calculate surface film as reported in the 1982 engineers' manual (LBL 1982) provides questionable values (as discussed in Section 3.2.4.1). Adjusting the surface film value or using various equations changes the percent difference from eQuest significantly, though a value or equation with low percent difference in all months was not found. It is likely this value that is causing the percent difference, though it cannot be determined for certain how eQuest calculates surface film coefficient.

3.3.2.2 Roof Conduction

Table 3-10 shows the roof conduction loads. The percent difference is poor. Like wall conduction, percent difference is higher in summer months though the absolute difference is lower in summer months. As with wall conduction the choice of surface film coefficient has a significant impact on the difference between eQuest and spreadsheet values, and is likely causing the variation. Applying the DOE-2 equation to the spreadsheet model (Section 3.2.4.1) results in low difference for every month. However the resulting surface film coefficients are unrealistically high.

Table 3-10: Roof conduction comparison results.

	Spreadsheet (kWh)	eQuest (kWh)	% Difference	Absolute Difference (kWh)
January	-6807	-7814	13%	1007
February	-5777	-6877	16%	1101
March	-4697	-5915	21%	1218
April	-2448	-3734	34%	1286
May	-362	-1629	78%	1267
June	1283	188	583%	1096
July	2054	1149	79%	904
August	1388	1015	37%	373
September	-331	-1079	69%	749
October	-2718	-3691	26%	974
November	-4430	-5160	14%	730
December	-6166	-7159	14%	992
Total	-29011	-40708	29%	11697

3.3.2.3 Underground Surface Conduction

Table 3-11 shows the underground surface conduction loads. There are a variety of methods to calculate underground surface conduction and it is not known which method DOE-2 applies. The difference in underground surface conduction numbers is good considering it is unknown how DOE-2 calculates this value since there is no up-to-date engineering manual for the DOE-2 program.

Table 3-11: Underground surface conduction comparison results.

	Spreadsheet (kWh)	eQuest (kWh)	% Difference	Absolute Difference (kWh)
January	-25650	-23424	-10%	2226
February	-23841	-23114	-3%	727
March	-25081	-25765	3%	684
April	-22280	-23938	7%	1659
May	-17646	-20608	14%	2962
June	-13059	-15967	18%	2908
July	-10699	-12936	17%	2237
August	-9845	-10679	8%	834
September	-10933	-10149	-8%	784
October	-14520	-12323	-18%	2197
November	-18215	-15285	-19%	2930
December	-22822	-19778	-15%	3045
Total	-214591	-213966	0%	625

3.3.2.4 Infiltration

Infiltration contributes to both the sensible and latent loads. Table 3-12 shows the sensible infiltration loads and Table 3-13 shows the latent infiltration loads. The difference in sensible infiltration loads is very low. The difference in latent infiltration loads is inconsistent. In both models, the latent infiltration load is only reported when there is a dehumidification load and not when humidification is required. It is unknown how eQuest calculates the latent load, so it is difficult to understand the variability in these values.

Table 3-12: Sensible infiltration comparison results.

	Spreadsheet (kWh)	eQuest (kWh)	% Difference	Absolute Difference (kWh)
January	-68463	-66829	-2%	1634
February	-61643	-59992	-3%	1651
March	-56873	-55339	-3%	1535
April	-40978	-40044	-2%	934
May	-28184	-27579	-2%	605
June	-14727	-14419	-2%	308
July	-8140	-8010	-2%	130
August	-10322	-10137	-2%	186
September	-20641	-20239	-2%	401
October	-36145	-35401	-2%	745
November	-45899	-44610	-3%	1288
December	-60873	-59295	-3%	1578
Total	-452888	-441892	-2%	10995

Table 3-13: Latent infiltration comparison results.

	Spreadsheet (kWh)	eQuest (kWh)	% Difference	Absolute Difference (kWh)
January	0	0	0%	0
February	0	0	0%	0
March	0	0	0%	0
April	0	117	100%	117
May	79	396	80%	317
June	2812	4067	31%	1255
July	7223	6967	-4%	257
August	6141	6256	2%	115
September	1442	1761	18%	319
October	175	585	70%	410
November	0	89	100%	89
December	0	30	100%	30
Total	17873	20267	12%	2394

3.3.2.5 Window Conduction

Table 3-14 shows the window conduction loads. The difference is very low in the winter and swing months and slightly higher in the summer months. As with the walls and roof, surface film coefficients could cause the variability in these values.

Table 3-14: Window conduction comparison results.

	Spreadsheet (kWh)	eQuest (kWh)	% Difference	Absolute Difference (kWh)
January	-14986	-14652	-2%	333
February	-13494	-13305	-1%	189
March	-12450	-12391	0%	58
April	-8970	-9000	0%	30
May	-6170	-6414	4%	244
June	-3224	-3560	9%	336
July	-1782	-2227	20%	446
August	-2260	-2680	16%	420
September	-4518	-4690	4%	172
October	-7912	-7953	1%	41
November	-10047	-9909	-1%	138
December	-13325	-13239	-1%	86
Total	-99136	-100021	1%	884

3.3.2.6 Window Solar Heat Gain

Table 3-15 shows the window solar heat gain loads. Differences are generally low, though the percent difference is higher in October, November and December. It is not known how DOE-2 and eQuest model ground reflectance as there is no up-to-date engineering manual for DOE-2. The spreadsheet uses a constant value of 0.2 for ground reflectance. It is possible that eQuest uses a different ground reflectance in the fall months.

Table 3-15: Window solar heat gain comparison results.

	Spreadsheet (kWh)	eQuest (kWh)	% Difference	Absolute Difference (kWh)
January	5453	5524	1%	71
February	6043	6313	4%	270
March	7000	7355	5%	355
April	7829	7956	2%	128
May	8777	8838	1%	61
June	9276	9220	-1%	57
July	9415	9303	-1%	112
August	9376	9210	-2%	165
September	8004	8625	7%	620
October	6430	7195	11%	765
November	3498	3946	11%	448
December	3604	4069	11%	466
Total	84704	87553	3%	2850

3.3.2.7 Occupants

Table 3-16 shows the sensible occupant heat gain loads and Table 3-17 shows the latent occupant heat gain loads. The difference in sensible heat gain values is very small for all months and can be attributed to rounding error. The difference in latent heat gain is small in summer months and large in winter months. The spreadsheet calculation multiplies the number of occupants in the building at each hour by the latent heat gain per person. The latent heat gain per person does not vary by time of year. However, the eQuest latent heat gain is much lower in winter months than in summer months. These numbers represent the building load and not the system load, so the interior humidity should not affect this calculation, though it may be that eQuest accounts for more thermal storage in the winter.

Table 3-16: Sensible occupant heat gain comparison results.

	Spreadsheet (kWh)	eQuest (kWh)	% Difference	Absolute Difference (kWh)
January	4766	4794	1%	28
February	4333	4358	1%	25
March	4766	4794	1%	28
April	4766	4794	1%	28
May	4549	4576	1%	27
June	4766	4794	1%	28
July	4983	5011	1%	29
August	4549	4576	1%	26
September	4766	4794	1%	28
October	4766	4794	1%	28
November	4549	4576	1%	27
December	4983	5012	1%	29
Total	56542	56871	1%	329

Table 3-17: Latent occupant heat gain comparison results.

	Spreadsheet (kWh)	eQuest (kWh)	% Difference	Absolute Difference (kWh)
January	4030	1975	-104%	2054
February	3663	1730	-112%	1933
March	4030	2661	-51%	1368
April	4030	3541	-14%	488
May	3846	3869	1%	22
June	4030	4053	1%	24
July	4213	4237	1%	24
August	3846	3869	1%	22
September	4030	4053	1%	24
October	4030	4033	0%	3
November	3846	3439	-12%	407
December	4213	2456	-72%	1756
Total	47805	39916	-20%	7888

3.3.2.8 Lights

Table 3-18 shows the lighting heat gain loads. The values are off by a consistent 8% each month. The two models have the same lighting power density input for the entire building. The spreadsheet does not include exterior lighting in this model, while it is unknown whether eQuest automatically adds exterior lighting to the model. Further, it is not known whether eQuest uses a ballast factor. It is also not known how eQuest calculates the building floor area; that is, whether it assumes the dimensions input by the user are exterior or interior dimensions. These could be reasons for the consistent 8% difference.

Table 3-18: Lighting heat gain comparison results.

	Spreadsheet (kWh)	eQuest (kWh)	% Difference	Absolute Difference (kWh)
January	10025	10885	8%	860
February	9114	9895	8%	781
March	10025	10884	8%	859
April	10025	10885	8%	859
May	9570	10390	8%	821
June	10025	10885	8%	860
July	10481	11379	8%	899
August	9569	10390	8%	820
September	10025	10885	8%	860
October	10025	10885	8%	859
November	9569	10390	8%	820
December	10481	11379	8%	899
Total	118933	129131	8%	10198

3.3.2.9 Equipment

Table 3-19 shows the equipment heat gain loads. Similar to the lighting results, values are off by a consistent 4% each month. The two models use the same equipment power density for the entire building. It is not known how eQuest calculates the building floor area from the user input dimensions. This may be a reason for the consistent 4% difference.

Table 3-19: Equipment heat gain comparison results.

	Spreadsheet (kWh)	eQuest (kWh)	% Difference	Absolute Difference (kWh)
January	14478	15038	4%	561
February	13161	13671	4%	509
March	14477	15038	4%	560
April	14478	15038	4%	560
May	13820	14355	4%	535
June	14477	15038	4%	561
July	15136	15721	4%	586
August	13819	14354	4%	535
September	14478	15038	4%	561
October	14478	15038	4%	561
November	13819	14354	4%	535
December	15136	15722	4%	586
Total	171756	178405	4%	6649

3.3.2.10 Total Load

Table 3-20 shows the total monthly loads from the two models. The percent and absolute differences vary significantly by month however the total percent difference is low.

Table 3-20: Total load comparison results.

	Spreadsheet (kWh)	eQuest (kWh)	% Difference	Absolute Difference (kWh)
January	-88570	-83558	-6%	5011
February	-78644	-75357	-4%	3287
March	-68662	-66929	-3%	1732
April	-41504	-41748	1%	244
May	-17942	-20122	11%	2180
June	8091	5701	42%	2390
July	21502	19733	9%	1768
August	16036	16279	-1%	243
September	-710	1980	-136%	2690
October	-29150	-24782	-18%	4368
November	-52123	-46427	-12%	5697
December	-75668	-69847	-8%	5821
Total Sensible	-407344	-385077	-6%	22267
Total Sensible and Latent	-341667	-324893	-5%	16774

It was seen throughout this exercise that the loads model values are reasonable but do vary in certain instances from the values calculated by eQuest. It is difficult to determine the reason for this variability because of the lack of documentation on DOE-2 and eQuest calculation methods. This exercise could be repeated using a better-documented program such as TRNSYS. However, it can be seen that the loads model provides reasonable results. Most importantly, the program presented here has documented all of the equations and assumptions used, which is one of its advantages relative to eQuest and DOE2.

3.4 Ventilation Loads Model

The ventilation loads are calculated on a separate sheet from the heating and cooling loads in order to clearly separate ventilation from space heating and cooling.

3.4.1 Ventilation Inputs

Inputs related to the ventilation system are entered directly on the ventilation loads sheet. The required ventilation inputs are,

- Ventilation rate per person and per m^2 floor area
- Minimum ventilation rate
- ERV and HRV efficiency

3.4.1.1 Ventilation Rates

The required ventilation rate for a space is governed by ASHRAE Standard 62.1. This standard gives the minimum required outdoor air ventilation rates per person and per m^2 floor area for a variety of occupancy types. The input for this program should be the average per person and per m^2 rate for the entire building. A better algorithm could be implemented to allow users to enter all of the various occupancy types with the corresponding floor area and ASHRAE ventilation rate. The program would then calculate the area-weighted average rate for the building.

A third ventilation rate must be entered, which is the minimum ventilation rate. This value is used when the building is unoccupied. This rate is not provided by ASHRAE-62, and in fact the minimum rate when the building is unoccupied should be the floor area ventilation rate. However, many buildings in practice lower ventilation rates when the building is unoccupied to save energy, and so a separate minimum value is included to model this practice.

3.4.1.2 HRV and ERV Efficiency

Heat recovery ventilators (HRV's) and energy recovery ventilators (ERV's) are common in buildings. These systems pass incoming outdoor air through a heat exchanger to recover energy from the exhaust air. HRV's recover only sensible heat, while ERV's recover both sensible and latent energy. The BELA program requires an efficiency to be input for both HRV and ERV; HRV represents the system's sensible heat recovery efficiency, and ERV the system's latent recovery efficiency. If there is only an HRV (therefore no latent heat recovery), the user should enter zero for ERV efficiency. If both are present, the efficiency would be entered in both cells.

3.4.2 Ventilation Load Calculations

The ventilation rate and heating or cooling load are calculated for each hour in the year.

3.4.2.1 Ventilation Rate

The ventilation rate per person and per m^2 floor area from the inputs section are used to calculate the total ventilation rate for the building,

$$\dot{Q} = R_p n_p + R_a A_{floor} \quad \text{Eq. 3-22}$$

Where $\dot{Q}$ = Required ventilation rate, l/s

R_p = People outdoor air rate, l/s-person

n_p = Number of people

R_a = Area outdoor air rate, l/s-m^2

A_{floor} = Floor area, m^2

In many buildings, the ventilation is reduced further during unoccupied hours. A minimum ventilation rate is entered by the user, and this value is used by the program when the building is unoccupied.

3.4.2.2 Ventilation Heating and Cooling Load

The sensible heating or cooling load due to ventilation air is,

$$Q_s = \eta_{HRV}\left[\dot{Q}\rho C_p (T_{out} - T_{in})\right] \quad \text{Eq. 3-23}$$

Where η_{HRV} = Heat Recovery Ventilator sensible efficiency, %

$\dot{Q}$ = Ventilation rate, l/s

ρ = Air density, kg/m^3

C_p = Specific heat capacity of air, J/kg-K

T_{out}, = Outdoor air temperature, K

T_{in} = Indoor air temperature, K

The model accounts for latent load only when latent heat removal is required (dehumidification). This assumes that there is no humidification present in the system, and so any latent heat addition (humidification) is ignored. Latent heat addition could easily be added if a humidification system were present. The latent cooling load due to ventilation air is,

$$\boldsymbol{Q_l = \eta_{ERV}\left[\dot{Q}(W_{out} - W_{in})(2501 + 1.805T_{in})\right]} \qquad \text{Eq. 3-24}$$

Where η_{ERV} = Energy Recovery Ventilator latent efficiency, %

W_{out} = Outdoor air absolute humidity, kgv/kga

W_{in} = Indoor air absolute humidity, kgv/kga

T_{in} = Indoor air temperature, °C

3.5 Loads Model Results

Loads results are displayed to allow users to see how their design decisions affect the building loads. Loads then direct the choice and sizing of the mechanical system. Displaying loads results prior to applying a mechanical system will allow architects to see how their decisions will directly affect the energy consumption of the building. For example, architects can try different levels of insulation and determine the optimal thickness based on cost payback.

The *Loads Results* sheet sums the heating and cooling loads calculated on the *Loads* and *Ventilation* sheets. There are three main tables: monthly heating loads, monthly cooling loads, and net monthly loads. These tables can be used to create whatever plot the user wishes to display. For example, January heating loads and August cooling loads may be displayed in pie charts to view what modes contribute the greatest to the heating and cooling loads (as in Figure 3-2 and Figure 3-3). Another useful graph may be a bar graph showing the total load each month, as in Figure 3-4.

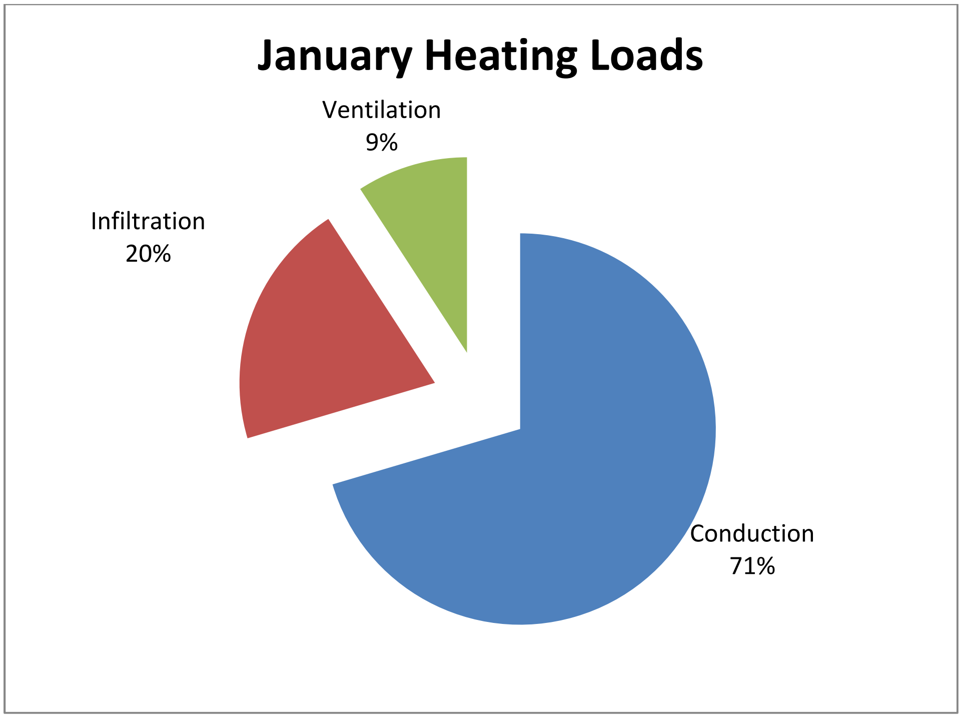


Figure 3-2: Sample loads results - January heating loads.

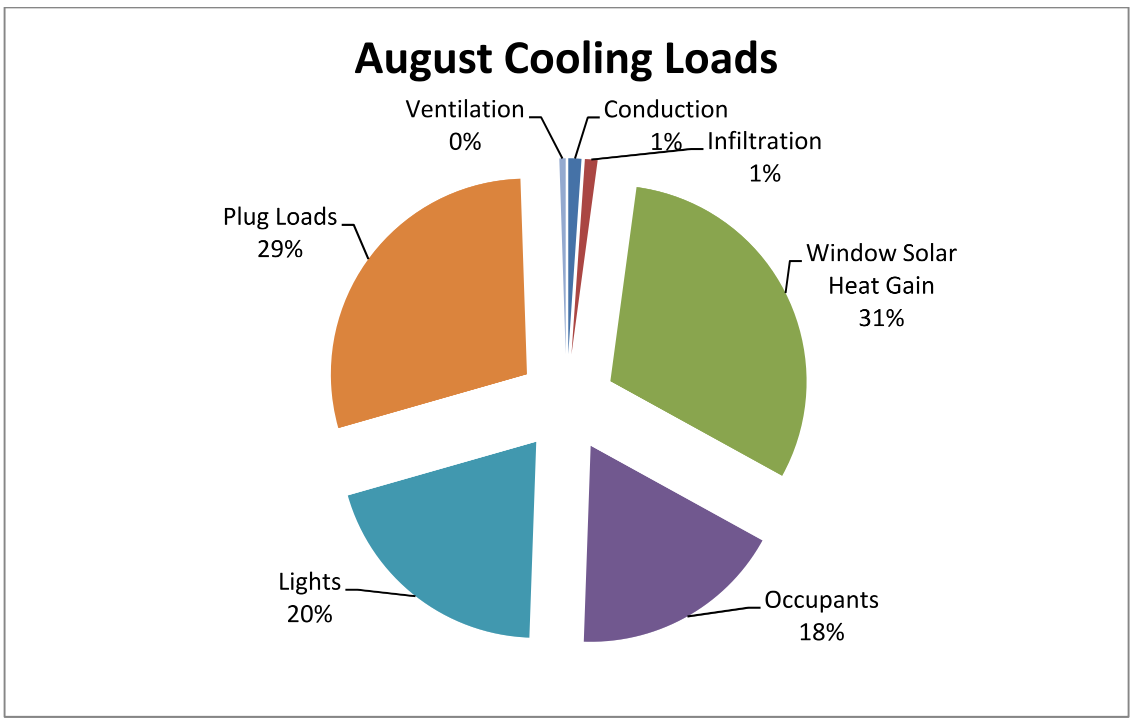


Figure 3-3: Sample loads results - August cooling loads.

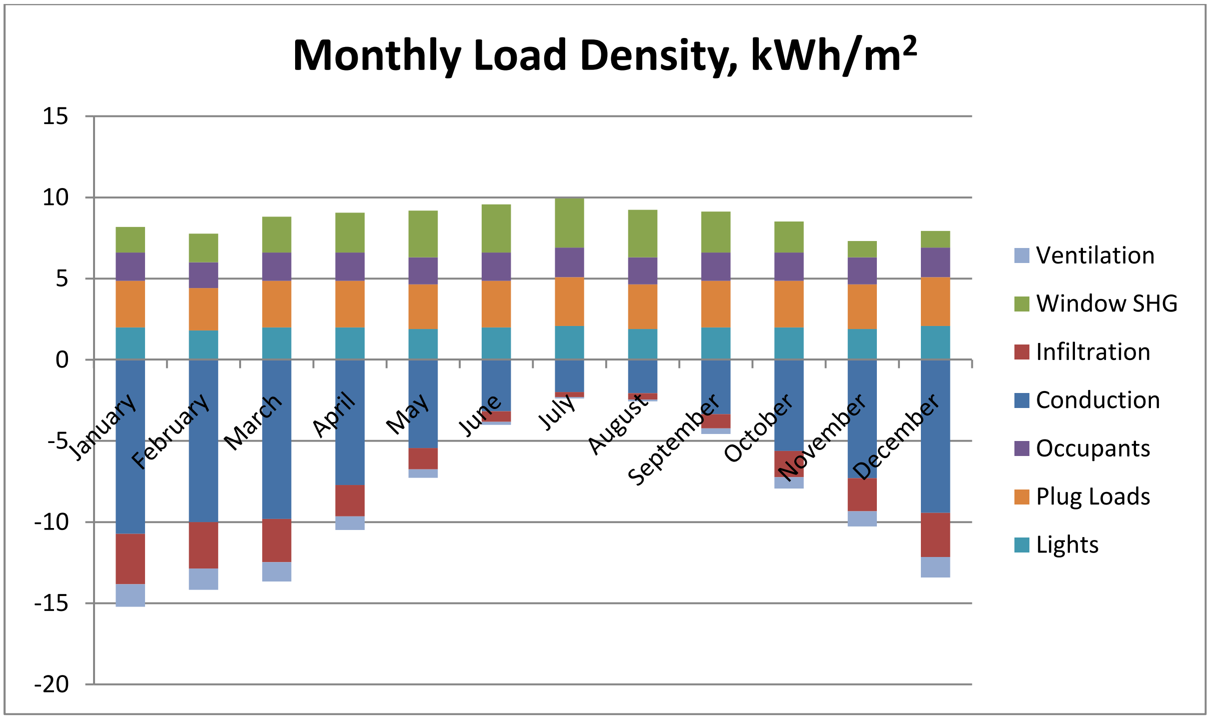


Figure 3-4: Sample loads results - monthly load density.

3.6 Summary

Given building inputs, weather data and schedules, the loads model calculates the space conditioning and ventilation loads at each hour for a year. The total heating or cooling load on the building at any time is comprised of conduction through all enclosure components, solar heat gain through windows, air infiltration, internal heat gains, and ventilation.

Many improvements could be implemented to make the loads model more accurate and more useable. Table 3-21 provides a list of recommended improvements discussed throughout the previous sections. The results of the loads model are used in the systems model to calculate actual energy use once mechanical system parameters have been selected.

Table 3-21: Recommended improvements to Loads model.

Section	Sub-Section	Description	Impact
Building Inputs	Dimensions	Automatic conversion of complex shapes, accounting for self-shading	Improve accuracy
Building Inputs	Enclosure	Calculate area-weighted average R-values and R-values	Improve ease of use
Building Inputs	Window Solar Heat Gain	Model exterior and interior shading, fixed and operable	Improve range of modeling capabilities
Building Inputs	Infiltration Rate	Algorithm to calculate hourly rate from wind speed data	Improve accuracy
Building Inputs	Occupant Density	Calculate area-weighted average occupant density	Improve accuracy and ease of use
Building Inputs	Lighting and Plug Load Density	Calculate area-weighted average lighting and plug load densities	Improve accuracy and ease of use
Building Inputs	Schedules	Add schedules for year, infiltration rate, indoor temperature, etc.	Improve accuracy
Loads Calculations	Conduction	Algorithm to calculate hourly exterior surface film coefficient.	Improve accuracy
Weighting Factors		Algorithm to select weighting factors based on user input thermal mass	Improve accuracy and ease of use
Weighting Factors		More accurate calculation to account for thermal mass	Improve accuracy
Other	Indoor Humidity	Hygrothermal model that includes moisture storage	Improve accuracy
Other	Domestic Hot Water	Add domestic hot water model	Improve accuracy

Chapter 4
HVAC Systems Models

4.1 Building HVAC Systems

HVAC systems typically serve two main functions: (1) Heat or cool the building and (2) Provide outdoor ventilation air to the building. In older buildings this is normally accomplished through a single system that combines heating and cooling with ventilation. Water is heated or cooled by a primary source such as a boiler or chiller. Hot or cold water is then passed through coils in an air handling unit where air is blown over the coils and becomes warmer or colder. The warm or cold air is then distributed to the building. A certain fraction of air is brought in from outside to serve as ventilation air, while the rest of the air is recirculated from the exhaust air. Figure 4-1 shows a schematic of this system.

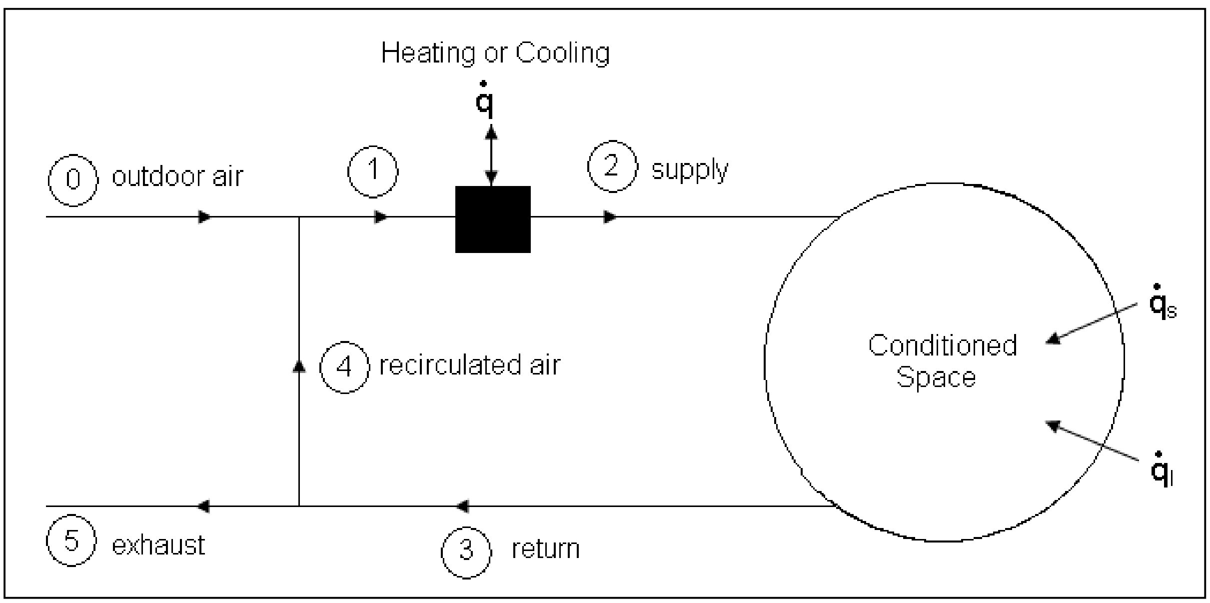


Figure 4-1: CAV or VAV system.

There are two common variations of this system, Constant Air Volume (CAV) and Variable Air Volume (VAV). CAV systems use a fixed portion of outdoor air and recirculated air, and always distribute the same constant volume of air to each space in the building. Variable air volume systems change the volume of air delivered to a space depending on the amount of heating or cooling required and the amount of ventilation required. CAV systems are extremely inefficient since they must be designed for peak load and therefore almost always move more air then required. CAV systems are rarely designed for new buildings. VAV systems are somewhat better and are still common in new buildings.

Deficiencies of VAV systems have been well documented in research (Mumma 1990; Kettler 1995; Mumma 1998). VAV systems are fundamentally limiting because they combine space conditioning with ventilation. In fact, ventilation and space conditioning often have opposite objectives. On a sunny winter day, an occupied office building may require little or no space heating but a significant amount of ventilation. At night when the building is unoccupied and there is no sun, heating is required but ventilation is not required. Situations may occur where not enough ventilation air is delivered in order to prevent over-heating or over-cooling, or too much ventilation air is delivered to meet space heating or cooling loads. Control algorithms for VAV systems become extremely complicated in order to avoid these scenarios.

Research indicates that the best approach to HVAC systems is to separate the heating and cooling system from the ventilation system (Mumma 2003; ASHRAE 2009). A Dedicated Outdoor Air System (DOAS) is a system that conditions and delivers outdoor ventilation air separately from space heating and cooling. In a DOAS system, there is no air recirculated through the building. A DOAS system can be used with any space heating and cooling system, such as radiant in-floor heating and cooling, radiant ceiling panels, chilled beams, fan coil units, and so on. DOAS systems are much easier to design and more reliable since they decouple ventilation supply from temperature control. They also use the minimum amount of energy to deliver ventilation air, allowing lower-energy systems to be used for space heating and cooling.

Currently, the system model simulates a DOAS system and two different space conditioning systems, radiant heating and cooling, and air handling units with fan coil units. CAV was not modeled as it is rarely used in new buildings, though this system could be created fairly easily. VAV was not modeled due to its complexity. A model for this system could be attempted, however it would be difficult since the system delivers a variable amount of fresh air, and may not always meet code ventilation requirements. A model for natural and hybrid ventilation will be discussed in Chapter 5.

4.2 Model Structure

The HVAC Systems model takes the results of the Loads model (Chapter 3) and applies various mechanical systems in order to determine the total annual building energy consumption. Each different system is modeled in parallel. There are currently two sheets: radiant heating and cooling with DOAS and air handling units with fan coil units and DOAS.

4.3 Dedicated Outdoor Air System

DOAS systems often involve multiple fans and non-linear duct paths with various losses. The details of the system are often not known until later design stages. Still, the energy consumption of these systems can be approximated by assuming a single, equivalent system with a single, equivalent airflow rate and pressure drop.

4.3.1 DOAS Inputs

Ventilation and DOAS inputs are entered on the Ventilation sheet and copied to the system sheets. The additional inputs required to calculate ventilation heating and cooling energy are,

- Heating source efficiency
- Cooling source efficiency

The inputs required to calculate fan power are,

- Fan and motor efficiency
- Maximum design fan airflow rate
- Maximum design fan pressure

4.3.1.1 Heating Source Efficiency

The heat source efficiency is the efficiency of the system that provides primary heating. This could be boiler efficiency (%), heat pump coefficient of performance (COP), furnace efficiency (%), or some other system.

4.3.1.2 Cooling Source Efficiency

The cooling source efficiency is the efficiency of the system that provides primary cooling. This could be a chiller COP, heat pump COP, air conditioner COP, or some other system.

4.3.1.3 Fan and Motor Efficiency

The fan and motor efficiencies are entered by the user (%). The total fan efficiency is calculated by multiplying the fan and motor efficiencies.

4.3.1.4 Maximum Design Fan Airflow Rate

The maximum design airflow rate is entered in litres per second (l/s). This value represents the total airflow rate designed for the entire system, even when multiple fans are present.

4.3.1.5 Maximum Design Fan Pressure

The maximum design fan pressure is entered in Pascals (Pa). This value represents the total pressure drop designed for the entire system, even when multiple fans and duct paths are present. This value is difficult to determine early in the design process. Alternatively, one could calculate the maximum design fan power allowed by ASHRAE 90.1-2004 (Energy Standard for Buildings) Appendix G (Performance Rating Method). Table G3.1.2.9 gives an equation for maximum baseline fan motor power as a function of maximum airflow rate, shown in Table 4-1. More efficient fans and motors can be used, and the data may be entered if and when known. The fan power and airflow rate can then be used to calculate the maximum design pressure drop,

$$\boldsymbol{P_f} = \frac{1000\,\eta\,Q_f}{\dot{Q}_{f,max}} \quad \text{Eq. 4-1}$$

Where $Q_{f,max}$ = Maximum design fan power, W

$\dot{Q}_{f,max}$ = Maximum design fan airflow rate, l/s

P_f = Maximum design fan pressure, Pa

η = Total fan efficiency, %

Table 4-1: ASHRAE 90.1 Appendix G fan power standard.

Supply Air Volume	*Baseline* Fan Motor Brake Horsepower: Constant Volume Systems 1 – 4	*Baseline* Fan Motor Brake Horsepower: Variable Volume Systems 5 – 8
< 9400 L/s	17.25 + (cfm - 20000) x 0.0008625	24 + (cfm - 20000) x 0.0012
≥ 9400 L/s	17.25 + (cfm - 20000) x 0.000825	24 + (cfm - 20000) x 0.001125

4.3.2 DOAS Calculations

4.3.2.1 Ventilation Heating and Cooling Energy

Outdoor air often must be heated, cooled or dehumidified before it can be distributed to the space. If heating is required,

$$\boldsymbol{Q} = \frac{\boldsymbol{Q_s}}{\boldsymbol{\eta_{heat}}} \qquad \text{Eq. 4-2}$$

Where Q = Energy to heat ventilation air, W

Q_s = Sensible ventilation heating load, W

η_{heat} = Heating source efficiency, % or COP

If sensible or latent cooling is required,

$$\boldsymbol{Q} = \frac{\boldsymbol{Q_s + Q_l}}{\boldsymbol{COP}} \qquad \text{Eq. 4-3}$$

Where Q = Energy to cool and dehumidify ventilation air, W

Q_s = Sensible ventilation cooling load, W

Q_l = Latent ventilation cooling (dehumidification) load, W

COP = Cooling source coefficient of performance

4.3.2.2 Fan Power

The maximum design fan power is calculated from the fan efficiency, maximum design airflow rate and maximum design pressure drop input by the user,

$$\boldsymbol{Q_{f,max}} = \frac{\boldsymbol{\dot{Q}_{f,max} P_f}}{\boldsymbol{1000 \eta_f \eta_m}} \qquad \text{Eq. 4-4}$$

Where $Q_{f,max}$ = Maximum design fan power, W

$\dot{Q}_{f,max}$ = Maximum design fan airflow rate, l/s

P_f = Maximum design fan pressure, Pa

η_f = Fan efficiency, %

η_m = Motor efficiency, %

Two common types of fans are on/off fans and variable speed drive fans (VSD, also known as variable frequency drive or VFD). On/off fans simply run at full speed and full power draw when ventilation is required and zero speed/power when ventilation is not required. The systems model program calculates energy consumption at one-hour intervals. To model on/off fans, it is assumed that the fan runs for the full hour when ventilation is required for that hour.

VSD fans vary the flow rate so that when less ventilation is required, less fan power is used. The theoretical power drawn by a VSD fan running at a lower-than-design rate can be calculated using fan laws,

$$\boldsymbol{Q_{f,i} = \frac{1}{\eta_f \eta_m} Q_{f,max} \left(\frac{\dot{Q}_i}{\dot{Q}_{f,max}}\right)^3} \qquad \text{Eq. 4-5}$$

Where $Q_{f,i}$ = Fan power draw at hour i, W

$Q_{f,max}$ = Maximum design fan power, W

$\dot{Q}_i$ = Ventilation rate at hour i, l/s

$\dot{Q}_{f,max}$ = Maximum design fan airflow rate, l/s

η_f = Fan efficiency, %

η_m = Motor efficiency, %

Fan relations for VSD power are theoretical because of additional losses from electronics. A more accurate model of VSD fan energy consumption would use a fan curve input from manufacturer's data to calculate fan energy consumption at each hour. Alternatively, this model uses the relation provided in ASHRAE 90.1-2004 Appendix G (G3.1.3.15),

$$\boldsymbol{P_{fan} = 0.0013 + 0.147 PLR_{fan} + 0.9506 PLF_{fan}^{\;2} - 0.0998 PLR_{fan}^{\;3}} \qquad \text{Eq. 4-6}$$

Where P_{fan} = Fraction of full load fan power

PLR_{fan} = Fraction of fan load (current load / design load)

4.4 Radiant Heating and Cooling

Radiant heating and cooling systems circulate heated or chilled water throughout a building to heat or cool the space. Two common forms of radiant systems are in-floor systems and ceiling panel systems. In-floor systems have tubes embedded in concrete floor slabs that run throughout the building flooring. Ceiling systems have metal panels dropped from the ceiling covering tubes for water. The water temperature that can be used with radiant in-floor cooling must be carefully selected so that condensation will not form on the floor. This limit also applies for ceiling systems, though it is often slightly better since heat transfer is not slowed by surface covers such as carpet, flooring or furniture.

Radiant heating and cooling has a number of benefits. Water-based radiant systems are generally more efficient than air-based systems since water has a higher specific heat capacity than air and therefore can transport heat more efficiently. Radiant heating systems operate with lower water temperatures since they have a large surface area over which heat exchange occurs. This means primary heating equipment such as heat pumps can operate more efficiently. Radiant systems are often more thermally comfortable than traditional air-based systems as they create a more uniform thermal environment. (Olesen 2008) Radiant systems also allow for the separation of heating and cooling from ventilation as discussed in Section 4.1.

4.4.1 Radiant Inputs

Radiant heating and cooling system inputs are entered directly on the radiant system sheet. The inputs required to calculate space heating and cooling energy are,

- Heating source efficiency
- Cooling source efficiency
- Pump and motor efficiency
- Heating and cooling temperature delta
- Maximum design heating and cooling pump flow
- Maximum design heating and cooling pump head

4.4.1.1 Heating and Cooling Source Efficiency

As with the DOAS system, the heat and cool source efficiencies are the efficiencies of the systems that provide primary heating and cooling, respectively. For heating this could be boiler efficiency (%), heat pump coefficient of performance (COP), furnace efficiency (%), or some other system. For cooling this could be a chiller COP, heat pump COP, air conditioner COP, or some other system.

4.4.1.2 Pump and Motor efficiency

The pump and motor efficiencies are entered by the user (%). The total pump efficiency is calculated by multiplying the pump and motor efficiencies.

4.4.1.3 Heating and Cooling Temperature Delta

The heating and cooling temperature delta is the difference in temperature between the supply and return water, in degrees Celsius. This value is typically about 10°C for heating and 3°C to 5°C for cooling in well designed, energy efficient systems (Olesen 2008). In cooling mode, condensation will form on the floor if the water through the radiant system is below the dew point temperature of the indoor air. This limits the temperature difference in cooling mode.

4.4.1.4 Maximum Design Heating and Cooling Pump Flow

The maximum design pump flow rate is entered in litres per second (l/s). This value represents the total flow rate designed for the entire system, even when multiple pumps are present. A different rate may be entered for heating and cooling mode.

In early design stages, this value is often not known. However, the required water flow rate can be calculated from the heating or cooling load and the water temperature delta,

$$\boldsymbol{Q_{load} = \dot{m}c_p\Delta T = \rho\dot{q}c_p\Delta T} \quad \text{Eq. 4-7}$$

$$\boldsymbol{\dot{q} = \frac{1000Q_{load}}{\rho c_p\Delta T}} \quad \text{Eq. 4-8}$$

Where $\dot{q}$ = Maximum design pump flow rate, l/s

Q_{load} = Maximum heating or cooling load, kW

ρ = Water density, kg/m^3

c_p = Specific heat capacity of water, 4.18 kJ/kg-K

ΔT = Heating or cooling temperature delta, K

4.4.1.5 Maximum Design Heating and Cooling Pump Head

The maximum design pump head is entered in metres. This value represents the total pressure drop designed for the entire system, even when multiple pumps are present. A different head may be entered for heating and cooling mode.

The design pump head is often unknown in early design stages of the building. Alternatively, maximum design pump energy can be estimated using ASHRAE 90.1-2004 Appendix G guidelines for pump power. This standard specifies that for a baseline building, hot water pumps should use less than 301 kW per 1000 l/s and chilled water pumps should use less than 349 kW per 1000 l/s. These values may be used to calculate maximum design pump head (McQuiston 2005),

$$\boldsymbol{H_p = \frac{1000\eta_p\eta_m W_{p,max}}{\dot{Q}_{p,max}\rho g}} \quad \text{Eq. 4-9}$$

Where H_p = Maximum design pump head, m

$\dot{Q}_{p,max}$ = Maximum design pump flow rate, l/s

$W_{p,max}$ = Maximum design pump power, W

ρ = Water density, kg/m^3

g = acceleration due to gravity, m/s^2

η_p = Pump efficiency, %

η_m = Motor efficiency, %

4.4.2 Radiant Calculations

4.4.2.1 Heating and Cooling Energy

The maximum heating and cooling that can be provided to the space is calculated from the user inputs (McQuiston 2005),

$$\boldsymbol{Q_{max} = \dot{m} c_p \Delta T} \qquad \text{Eq. 4-10}$$

Where Q_{max} = Maximum heating or cooling, W

$\dot{m}$ = Mass flow rate of water, kg/s

c_p = Specific heat capacity of water, kJ/kg-K

ΔT = Difference between supply and return water temperature, °C

The amount of heating or cooling energy required to condition the space for a given hour is calculated from the load and the source heating or cooling efficiency. When heating is required,

$$\boldsymbol{Q = \frac{Q_s}{\eta_{heat}}} \qquad \text{Eq. 4-11}$$

Where Q = Energy to heat space, W

Q_s = Sensible space heating load, W

η_{heat} = Heating source efficiency, % or COP

When cooling or dehumidification is required,

$$\boldsymbol{Q = \frac{Q_s + Q_l}{COP}} \qquad \text{Eq. 4-12}$$

Where Q = Energy to cool and dehumidify space, W

Q_s = Sensible space cooling load, W

Q_l = Latent space cooling (dehumidification) load, W

COP = Cooling source coefficient of performance

4.4.2.2 Pump Power

The maximum required pump power is calculated from the design pump flow and head (McQuiston 2005),

$$\boldsymbol{W_{p,max} = \frac{\dot{Q}_{p,max}\rho H_p g}{1000\eta_p\eta_m}} \quad \text{Eq. 4-13}$$

Where $W_{p,max}$ = Maximum design pump power, W

$\dot{Q}_{p,max}$ = Maximum design pump flow rate, l/s

ρ = Water density, kg/m^3

H_p = Maximum design pump head, m

g = acceleration due to gravity, m/s^2

η_p = Pump efficiency, %

η_m = Motor efficiency, %

As with fans, pumps can be on/off or variable speed drive (VSD). A VSD pump model is currently not included but should be developed for future versions. Pump energy is calculated at one-hour intervals, though on/off pumps will not run for the full hour when a fraction of the maximum heating or cooling load is required. To model this, it is assumed that the pump runs for a fraction of the hour proportional to the percent of the maximum heating or cooling required. That is,

$$\boldsymbol{W_p = W_{p,max}\frac{Q_{load}}{Q_{max}}} \quad \text{Eq. 4-14}$$

Where W_p = Pump power at given hour, W

$W_{p,max}$ = Maximum design pump power, W

Q_{load} = Heating or cooling load at given hour, W

Q_{max} = Maximum design heating or cooling load, W

4.5 Air Handling Units and Fan Coil Units

A fan coil (FC) unit blows air from a room over coils. Hot or cold water is circulated through the coils so that air from the room is heated or cooled. Fan coil units are often installed above dropped ceilings or along exterior walls. Air handling units (AHU's) are typically larger versions of fan coil units that serve larger spaces. These systems are typically much less expensive than radiant systems, still allow for the separation of heating and cooling from ventilation, and can be nearly as efficient when well designed. This system as a few drawbacks compared to radiant systems. Fan coil units require regular maintenance as the filter must be changed, typically about once per year. They make some noise, and have moving parts near occupied spaces that could require maintenance.

4.5.1 AHU/FC Inputs

Both the AHU/FC and radiant systems have a pump that moves heated or chilled water. From an energy modeling standpoint, the primary difference between the AHU/FC system and the radiant system is that AHU/FC requires additional fan power to move air over heating or cooling coils. This means the AHU/FC system requires inputs for both pumps and fans. The inputs required to calculate space heating and cooling energy for this system are,

- Heating source efficiency
- Cooling source efficiency
- Pump and motor efficiency
- Heating and cooling temperature delta
- Maximum design heating and cooling pump flow
- Maximum design heating and cooling pump head
- Fan and motor efficiency
- Maximum design fan airflow rate
- Maximum design fan pressure
- Number of fan coil units

4.5.1.1 Heating and Cooling Source Efficiency

As with the DOAS and radiant systems, the heat and cool source efficiencies are the efficiencies of the systems that provide primary heating and cooling, respectively. For heating this could be boiler efficiency (%), heat pump coefficient of performance (COP), furnace efficiency (%), or some other system. For cooling this could be a chiller COP, heat pump COP, air conditioner COP, or some other system.

4.5.1.2 Pump and Motor efficiency

The pump and motor percent efficiencies are entered. The total pump efficiency is calculated by multiplying the pump and motor efficiencies.

4.5.1.3 Heating and Cooling Temperature Delta

The heating and cooling temperature delta is the difference in temperature between the supply and return water, in degrees Celsius. These values are higher for FC systems than for radiant systems since the surface area over which heat exchange occurs is much smaller.

4.5.1.4 Maximum Design Heating and Cooling Pump Flow

The maximum design pump flow rate is entered in litres per second (l/s). This value represents the total flow rate designed for the entire system, even when multiple pumps are present. A different rate may be entered for heating and cooling mode. As with radiant systems, if pump flow is unknown at the time of simulation, a value can be estimated using the procedure in Section 4.4.1.4.

4.5.1.5 Maximum Design Heating and Cooling Pump Head

The maximum design pump head is entered in metres. This value represents the total pressure drop designed for the entire system, even when multiple pumps are present. A different head may be entered for heating and cooling mode. As with radiant systems, if pump head is unknown at the time of simulation, a value can be estimated using the procedure in Section 4.4.1.5.

4.5.1.6 Fan and Motor Efficiency

The fan and motor efficiencies of the FC fans are entered by the user (%). The total fan efficiency is calculated by multiplying the fan and motor efficiencies.

4.5.1.7 Maximum Design Airflow Rate

The maximum design airflow rate is entered in litres per second (l/s). This value represents the maximum airflow rate of a single FC fan, even when multiple FC units are present.

4.5.1.8 Maximum Design Fan Pressure

The maximum design fan pressure is entered in Pascals (Pa). This value represents the maximum fan pressure of a single FC fan, even when multiple FC units are present. If this value is unknown at the time of simulation, it can be estimated using the procedure in Section 4.3.1.5.

4.5.1.9 Number of Fan Coil Units

The number of FC units in the building is entered. The energy consumption of one FC unit calculated from the user inputs for fan pressure and airflow rate is multiplied by the total number of FC units in the building.

4.5.2 AHU/FC Calculations

4.5.2.1 Heating and Cooling Energy

The heating and cooling energy is calculated as for radiant systems (Section 4.4.2.1 Heating and Cooling Energy).

4.5.2.2 Pump Power

Pump power is calculated as for radiant systems (Section 4.4.2.2 Pump Power). Only on/off pumps are currently modeled; a VSD pump model should be added.

4.5.2.3 Fan Power

The maximum fan power is calculated for a single FC unit and multiplied by the number of FC units to obtain the maximum fan power for the entire building. The fan power calculation is the same as that used for DOAS (Section 4.3.2.2 Fan Power).

4.6 Systems Model Results

Results from the systems model are displayed to allow users to see the total building energy consumption. In the program, the *Systems Results* sheet sums the hourly energy calculated on each of the systems sheets, currently *Radiant DOAS* and *Fan Coil DOAS*. The *Systems Results* sheet displays a table for each system configuration that displays the total energy consumption by category (eg. space heating, ventilation distribution, lighting, etc.) for each month. These tables can be used to create plots to display results graphically. For example, the energy consumption of a single system over the course of a year can be viewed, as in Figure 4-2. The annual energy consumption of different mechanical systems can be compared, as in Figure 4-3.

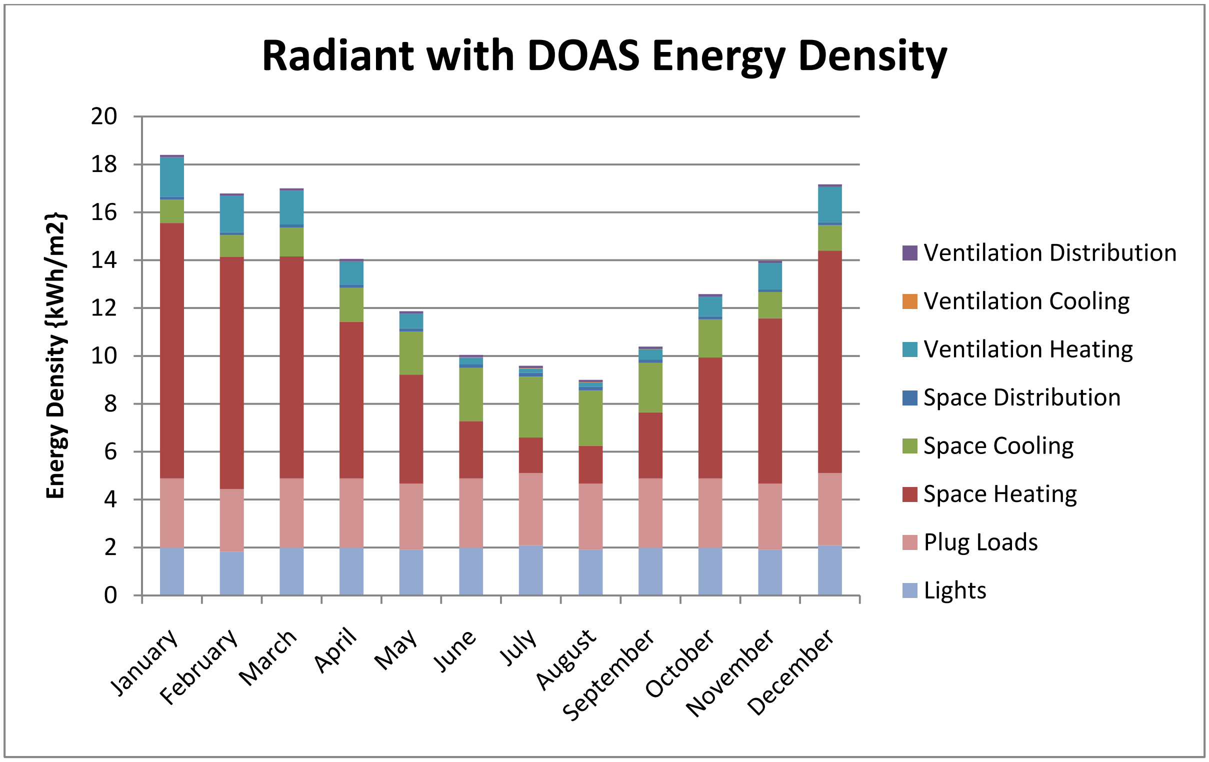


Figure 4-2: Energy consumption for radiant heating/cooling system with dedicated outdoor air.

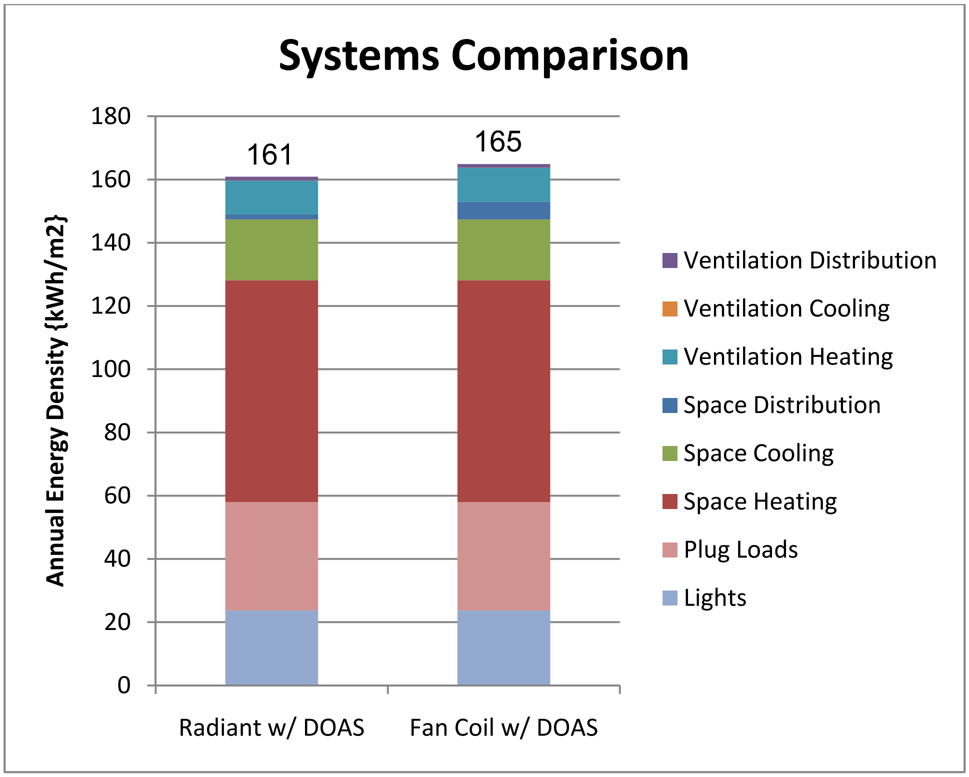


Figure 4-3: Systems energy comparison.

4.7 Summary

Energy models for two common heating and cooling systems have been created; radiant heating and cooling, and fan coil units. These systems are modeled with a dedicated outdoor air system (DOAS) to provide ventilation.

Many improvements could be implemented to expand the systems model portion of this program. Table 4-2 provides a list of recommended improvements discussed in the previous sections.

Table 4-2: Recommended improvements to systems model.

Section	Description	Impact
General	Add more HVAC systems models	Improve range of modeling capabilities
General	Attempt VAV model	Improve range of modeling capabilities
Radiant, FC/AHU	Implement pump VSD model	Improve accuracy and range of modeling capabilities
DOAS	Implement economizer model	Improve accuracy and range of modeling capabilities

Chapter 5

Application: Natural and Hybrid Ventilation

The program developed thus far can be used as a basis for modeling energy consumption of new and innovative systems. One such system is natural or hybrid ventilation. Background information on ventilation will be presented in this chapter, while the energy model for natural ventilation will be presented in Chapter 6.

5.1 What is Ventilation?

ASHRAE defines ventilation as “the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space” (ASHRAE 2007). Ventilation can serve three purposes:

(1) To provide oxygen for occupants to breathe (and remove CO2)

(2) To dilute odors generated within the building

(3) To cool the building (“free cooling”)

The amount of ventilation provided to a space is measured in volume of air flow per unit time, usually in litres per second (l/s) or cubic feet per minute (cfm). Each of the three purposes listed above requires a different amount of ventilation. The amount of ventilation for (1) and (2) are combined and required by code to ensure a healthy indoor air quality. In Ontario, these ventilation rates are given in ASHRAE Standard 62, which is referenced by the Ontario Building Code.

Ventilation rates to provide cooling to a space are more difficult to quantify. When outdoor air temperatures are lower than the indoor design temperature, outdoor ventilation air can be circulated through the building to offset internal heat gains. Even when outdoor temperatures are higher than the indoor design temperature, elevated airflow rates can make occupants feel comfortable in warmer temperatures. The amount of this ventilation cooling available to a building is limited by air speed and climate.

There are two traditional approaches to providing ventilation to a space: mechanical (forced) ventilation and natural ventilation. Mechanical ventilation is the intentional movement of air into and out of a building using fans and intake and exhaust vents.

Natural ventilation is the flow of air through open windows, doors, grilles, and other planned penetrations driven by natural pressure differentials. Natural ventilation is desirable since it does not use energy and does not require ductwork. However in practice a building that relies only on natural ventilation is extremely difficult to achieve since it is limited by building layout and weather. The building layout must be such that all occupied spaces receive ventilation, and the design must ensure that there is enough driving force to provide adequate ventilation during all occupied hours. The outdoor air conditions restrict the use of natural ventilation; cold air must be heated before it is brought into the building and humid air must be dried if it is to be comfortable when it enters the occupied space. In southern Ontario natural ventilation is most useful during swing seasons, fall and spring, when outdoor temperatures are close to indoor temperatures.

Servicing a building with natural ventilation alone is often not possible. Hybrid ventilation is a term used to describe some combination of natural and mechanical ventilation. A hybrid ventilation system could consist of a full mechanical ventilation system supplemented by operable windows or a primarily natural ventilation system with fans to achieve required airflow rates. Hybrid ventilation may operate a mechanical system only during certain times of year (eg. heating and cooling seasons) or certain hours of the day (eg. peak load hours) and rely on natural ventilation at other times. Hybrid ventilation has the potential to minimize energy used for ventilation yet eliminate the obstacles of natural ventilation.

Buildings that rely entirely on natural ventilation for outdoor ventilation air are uncommon, particularly in southern Ontario. A number of buildings employ a hybrid ventilation system, often in the form of a full mechanical ventilation system supplemented by operable windows. These systems may reduce energy consumption if the building has demand-controlled ventilation; natural ventilation will reduce CO2 levels inside the building, allowing the mechanical system to automatically run at a lower rate. However such hybrid ventilation systems may neither provide ventilation air nor save energy if they are not designed properly.

Many residential buildings rely on “free cooling”, though this typically means they have operable windows and no air conditioner and can become quite hot during summer months. A well-established method of free cooling is the economizer, which brings in outdoor air through ducts, driven by fans, to cool the building when the outdoor air temperature and humidity are sufficiently low. While the economizer does provide free cooling, it still requires fan energy to distribute the air, and it is limited by the capacity of the ventilation system. Some buildings have been designed to maximize natural ventilation for the purpose of free cooling. Even with mechanical cooling, natural ventilation for free cooling can reduce energy loads by cooling the building during swing seasons or during hours with peak internal heat gains, minimizing the amount of time that mechanical cooling runs.

The benefit of natural and hybrid ventilation systems is that they have the potential to reduce energy consumption in a building. The first step in natural ventilation design should be to determine how much energy it can save. Buildings with energy-efficient mechanical systems such as radiant heating and cooling with dedicated outdoor air ventilation systems may have extremely low ventilation energy requirements. This could mean that efforts may be better spent minimizing energy used for other parts of the building.

Calculating potential energy savings from natural or hybrid ventilation is difficult. Many current energy modeling software programs do not facilitate the investigation of natural ventilation among energy efficiency measures. To do this, one must be able to separate space heating and cooling loads from ventilation loads. This is possible with the program that has been developed through this project.

The main concern with natural ventilation is being able to meet standards for ventilation airflow rates. These standards will first be discussed. Methods for calculating natural ventilation airflow will be presented. Finally, a natural and hybrid ventilation model will be presented in order to determine how much energy this system would use compared to an efficient mechanical system such as a DOAS.

5.2 Current Standards and Practice

Ventilation is important for both occupant health and comfort. There are a number of standards and codes in the building industry that have requirements or guidelines on ventilation. Three important standards from the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) are,

- ASHRAE 55: Thermal Environmental Conditions for Human Occupancy
- ASHRAE 62: Ventilation for Acceptable Indoor Air Quality
- ASHRAE 90: Energy Standard for Buildings

Building codes also provide ventilation requirements, including the Ontario Building Code (OBC) and the National Building Code of Canada (NBCC). Many industries provide standards with ventilation requirements specific to their building occupancies such as health care facilities and animal facilities. These buildings often require higher airflow rates and are beyond the scope of this project. The LEED (Leadership in Energy and Environmental Design, USGBC) rating system has two credits that deal specifically with ventilation.

5.2.1 ASHRAE 55: Thermal Environmental Conditions for Human Occupancy

ASHRAE 55 specifies conditions that will be thermally comfortable for the majority of building occupants in both mechanically and naturally conditioned spaces. In mechanically ventilated spaces, a thermal comfort zone is determined graphically, as shown in Figure 5-1. An air temperature and humidity that lies within the "1.0 Clo" shaded region will be comfortable for the average office worker ("Clo" refers to the clothing level of the occupants). Other building types will have different comfort zones depending on the clothing level and activity level of the occupants. Figure 5-1 shows that temperatures between 19° C and 26° C are comfortable for the average office worker, so mechanical systems should be designed to keep the air temperature within this range.

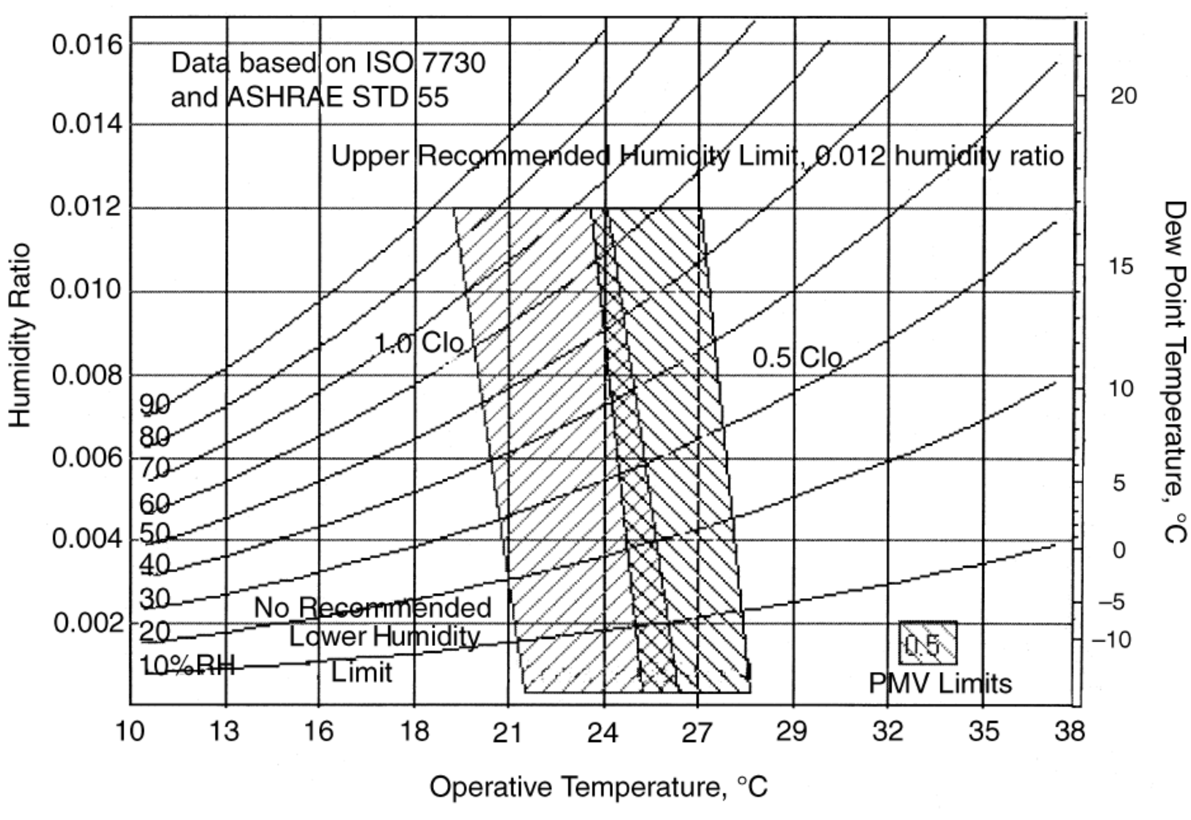


Figure 5-1: Acceptable range of temperature and humidity (ASHRAE 55).

It is important to recognize that these acceptable ranges are for 80% occupant acceptability. ASHRAE recognizes that some occupants (about 20%) will still be uncomfortable within this range. The chart also does not provide a recommended lower humidity limit, yet occupants would likely be uncomfortable in a very dry, low relative humidity (RH). Even the upper recommended humidity limit can be over 90% RH, which could cause condensation in the building or wall assembly under certain conditions. Summer and winter comfort conditions will also be different since occupants tend to be comfortable in slightly cooler indoor temperatures in the winter and warmer indoor temperatures in the summer.

All conditioned spaces must also meet requirements for local thermal discomfort including drafts, radiant temperature asymmetry, vertical air temperature difference, floor surface temperature, and temperature variations with time.

The most recent version of ASHRAE 55 includes a section on thermal comfort for naturally conditioned spaces. This is in response to studies showing that occupants are comfortable in a wider range of temperatures in naturally conditioned spaces (Brager 2000). ASHRAE 55 defines naturally conditioned spaces as spaces with no mechanical cooling system, where opening and closing windows is the primary means of regulating thermal conditions. For this approach to apply there must be no mechanical cooling system for the space (there may be mechanical ventilation with unconditioned air). Further, the mean monthly outdoor air temperature must be between 10° C and 33° C and all spaces must have operable windows accessible to the occupants. This would apply for four to six months in most major Canadian cities (six months in Toronto, Hamilton and Vancouver; five months in Montreal, Ottawa and Edmonton; and four months in Halifax and Calgary).

Like mechanically conditioned spaces, the standard gives a graph of acceptable temperature ranges for thermal comfort (Figure 5-2). Figure 5-2 shows that 80% of occupants will be comfortable at indoor temperatures up to 31° C.

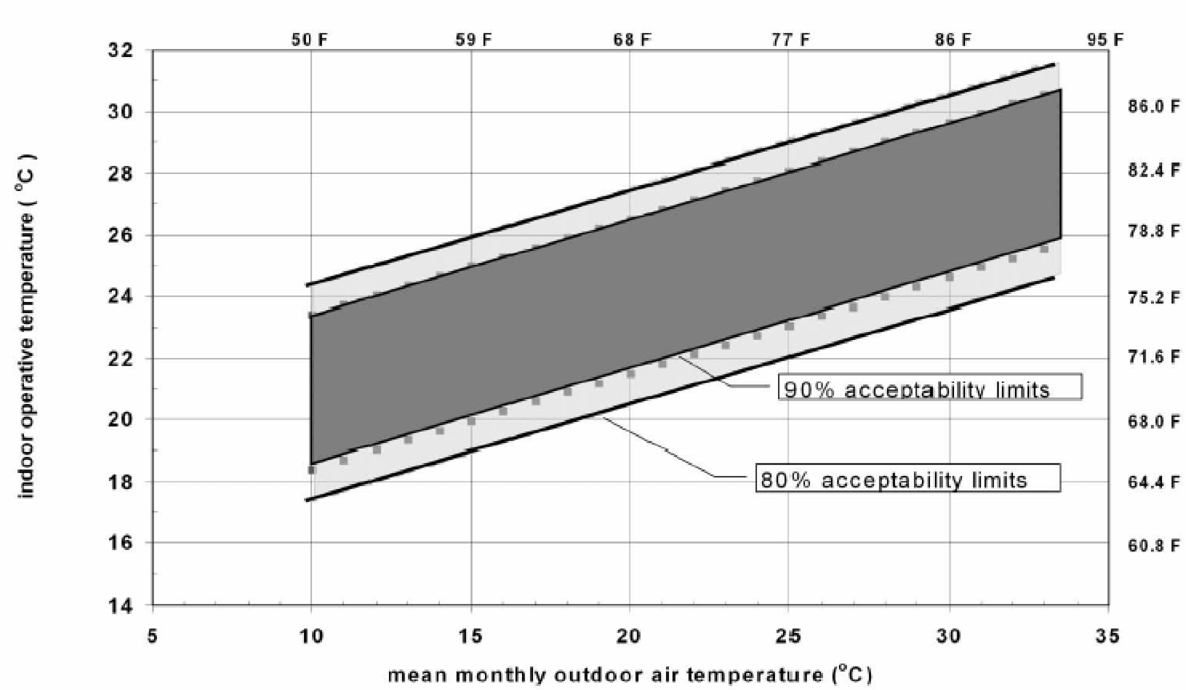


Figure 5-2: Acceptable operative temperature ranges for naturally conditioned spaces.

5.2.2 ASHRAE 62.1: Ventilation for Acceptable Indoor Air Quality

ASHRAE 62 provides ventilation system requirements for good indoor air quality in occupied building spaces. There are two standards, 62.1 deals with commercial buildings and 62.2 deals with residential buildings. The most recent version of ASHRAE 62.1 was released in 2007. This standard specifies requirements for outdoor air quality, systems and equipment, procedures for calculating airflow rates, construction and start-up, and operation and maintenance. There are a number of requirements that apply to both naturally and mechanically ventilated systems such as air intake locations, airstream surface mold and erosion resistance, controls, construction start-up and operation and maintenance. The most commonly referenced sections of ASHRAE 62.1 are the opening requirements for naturally ventilated spaces and the airflow requirements for mechanically ventilated spaces.

ASHRAE 62.1 defines natural ventilation as ventilation provided by thermal, wind, or diffusion effects through doors, windows or other intentional openings in the building. Naturally ventilated spaces must be within 8 m (25 ft) of operable wall or roof openings to the outdoors. The openable area must be at least 4% of the net occupiable floor area. Interior spaces without direct openings to the outdoors can be ventilated through adjoining rooms provided the opening between rooms is at least 8% of the interior room floor area and not less than 2.3 m^2 (25 sf). Building occupants must be able to access all natural ventilation openings.

Mechanical systems can be designed using one of two procedures: the IAQ procedure or the ventilation rate procedure. Using the IAQ procedure, the system is designed to keep the concentration rate of certain contaminants below specified limits. The ventilation rate procedure is most commonly used and will be discussed here.

The ventilation rate procedure gives the minimum airflow rate (in cubic feet per minute or litres per second) that must be delivered to each occupied space. ASHRAE tables provide the required airflow rate per person and per square metre (or square foot) of floor area for a variety of occupancy types. The total airflow required to ventilate each space is the sum of the rate per person plus the rate per m^2 floor area. Systems can also be designed to vary the airflow rate depending on occupancy conditions, for example using CO_2 sensors or occupancy schedules.

For example, Table 6.1 in ASHRAE 62.1 specifies an airflow rate of 2.5 l/s per person plus 0.3 l/s per m^2 for office space. A 100 m^2 office designed for 10 people would require 2.5 x 10 + 0.3 x 100 = 55 l/s. Classrooms are required to have 5 l/s per person plus 0.6 l/s per m^2 floor area. A 100 m^2 classroom designed for 35 people would require 5 x 35 + 0.6 x 100 = 235 l/s. These requirements do not apply to naturally ventilated spaces.

ASHRAE 62.1 requires mechanical ventilation systems to have manual or automatic controls such that the system operates whenever the space is occupied. This could be a continuous system that runs all hours of the day, an occupancy schedule that turns on in the morning and off at night, occupancy sensors or some other control method.

ASHRAE 62.2 provides separate ventilation guidelines for low-rise residential buildings (three stories or fewer). This standard requires 3.5 l/s per person plus 0.05 l/s per m^2 floor area. This can be compared to the ASHRAE 62.1 guidelines for high-rise residential buildings (four stories or more), 2.5 l/s per person plus 0.3 l/s per m^2. This means dwelling units in low-rise buildings require less ventilation airflow than units in high-rise buildings.

5.2.3 ASHRAE 90.1: Energy Standard for Buildings

ASHRAE 90 specifies minimum energy performance criteria for various building components. It provides minimum insulation values for all parts of the building envelope and efficiencies for mechanical and electrical systems. As with Standard 62, there are two versions of Standard 90; 90.1 is for commercial buildings and 90.2 is for residential buildings.

This standard requires that an energy recovery ventilation system must be used if more than 3000 cfm and 70% outside air will be delivered at minimum outdoor design conditions. Ductwork and plenums must be insulated to minimum levels. HVAC systems with a capacity greater than 10,000 cfm (4700 L/s) must have controls to start the system just before scheduled occupancy. ASHRAE 90.1 also gives limits on fan power (Table 5-1) and fan speed control. It should be noted that ASHRAE 90.1 is currently undergoing major changes to tighten energy standards for buildings.

Table 5-1: Fan power limitation (ASHRAE 90.1 Table 6.3.3.1)

Supply Air Volume	Allowable Nameplate Motor Power	
	Constant Volume	Variable Volume
< 20,000 cfm	1.2 hp / 1000 cfm (1.1 cfm / W)	1.7 hp / 1000 cfm (0.8 cfm / W)
> 20,000 cfm	1.1 hp / 1000 cfm (1.2 cfm / W)	1.5 hp / 1000 cfm (0.9 cfm / W)

5.2.4 Ontario Building Code

The Ontario Building Code (OBC) creates challenges to natural ventilation design due to fire protection requirements. Openings between building spaces must be controlled to prevent smoke from spreading in the event of a fire. A fire separation is a construction assembly that acts as a barrier against the spread of fire. Adjoining spaces with different occupancy types must be fire separated. Other fire separation requirements vary depending on occupancy type, but floor assemblies and load-bearing walls are usually required to be fire separations.

Fire separations become an issue when designing openings through floor assemblies for natural ventilation, such as an atrium (called interconnected floor space). The OBC defines interconnected floor space as area in which floor assemblies that are required to be fire separations are penetrated by openings that are not provided with closures. In general, interconnected floor openings must have a cross-sectional area that can contain a 9m diameter circle or an ellipse 7m wide along the minor axis and at least 65m^2 in area (Figure 5-3). There are exceptions and provisions for specific occupancies. For example, interconnected floor space of two stories is permitted in elementary and secondary schools (without a minimum cross-sectional area). The OBC fire code requirements may create design challenges for naturally ventilated buildings. However it should not prohibit the use of natural ventilation.

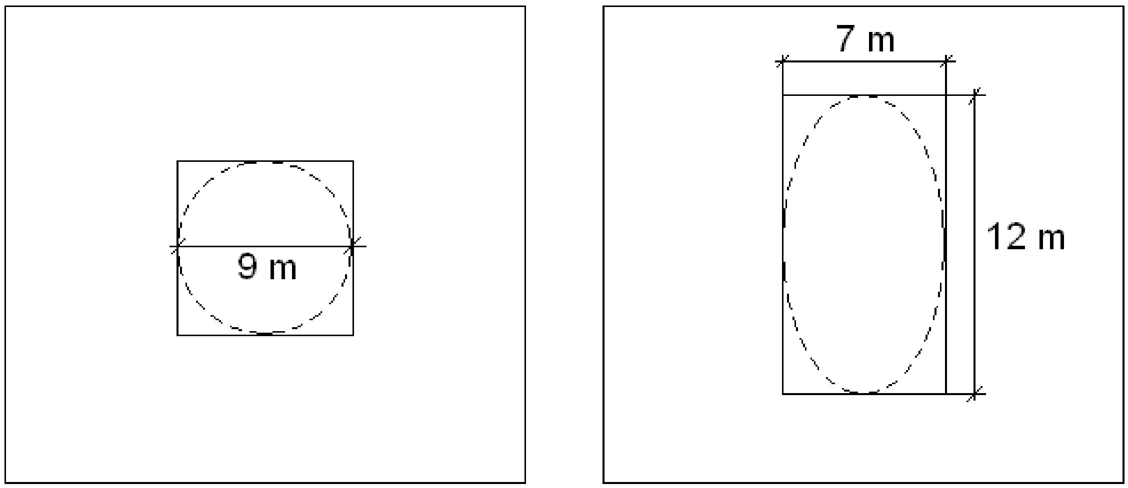


Figure 5-3: Minimum atrium dimensions for OBC fire protection code.

The OBC requires outdoor air ventilation rates in accordance with ASHRAE 62. Natural ventilation may be used in buildings other than residential occupancy where the occupant load is less than one person per 40 m^2, or where engineering data demonstrates that it will provide adequate ventilation. In residential buildings that are naturally ventilated, the openable ventilation area to the outdoors must meet the minimum areas in Table 5-2. Most rooms require an opening area of 0.28 m^2. By comparison, ASHRAE requires exterior openings to be at least 4% of the net occupiable floor area. The OBC standard is less stringent than ASHRAE for any room with a floor area greater than 7 m^2 (since a 7 m^2 room would require an opening area of 7 x 0.04 = 0.28 m^2 by ASHRAE standards). For example, a 5m by 5m bedroom would have an opening area that is 1% of the floor area.

For mechanically ventilated residential buildings the OBC gives a set of standards including minimum airflow requirements. Alternatively, residential buildings may comply with ASHRAE 62. The OBC requires 10 L/s of airflow in the master bedroom and the basement and 5 L/s in all other rooms. ASHRAE 62 requires 2.5 L/s per person plus 0.3 L/s per m2 to all rooms. A residential unit designed for two people would require 2 x 2.5 = 5 L/s plus the additional 0.3 L/s per m2 floor area. This means ASHRAE 62 will usually be more stringent than the OBC requirement for ventilation airflow.

Table 5-2: Natural ventilation opening area requirements for residential buildings in OBC.

Location		Minimum Area
Within a dwelling unit	Bathrooms or water closet rooms	0.09 m^2 (1 sf)
	Unfinished basement space	0.2% of the floor area
	Dining rooms, living rooms, bedrooms, kitchens, combined rooms, dens, recreation rooms and all other finished rooms	0.28 m^2 (3 sf) per room or combination of rooms
Other than within a dwelling unit	Bathrooms or water closet rooms	0.09 m^2 (1 sf) per water closet
	Sleeping areas	0.14 m^2 (1.5 sf) per occupant
	Laundry rooms, kitchens, recreation rooms	4% of the floor area
	Corridors, storage rooms and other similar public rooms or spaces	2% of the floor area
	Unfinished basement space not used on a shared basis	0.2% of the floor area

5.2.5 National Building Code of Canada

The National Building Code of Canada (NBCC) is very similar to the OBC (Canada 2005). The three sections related to ventilation are Section 3 (Fire), Section 6 (HVAC) and Section 9 (residential and small buildings). Occupancy classifications are identical to those in the OBC.

Sections 3 and 6 of the NBCC are very similar to the OBC with only minor differences. In Section 9, the NBCC and OBC differ in when mechanical ventilation is required. The OBC requires mechanical ventilation for each dwelling unit that is supplied with electrical power. The NBCC is divided into heating season and non-heating season ventilation. Non-heating season ventilation can be by natural or mechanical means. Like the OBC, heating-season ventilation must be mechanical if the dwelling unit is supplied with electrical power.

5.2.6 LEED

There is one prerequisite and one credit in LEED directly related to ventilation. Indoor Environmental Quality (IEQ) Prerequisite 1: Minimum IAQ performance requires buildings meet ASHRAE 62-2001. IEQ Credit 2: Ventilation effectiveness varies in different versions of LEED. LEED Canada and LEED USA v2.1 and older have the following requirements:

“For mechanically ventilated buildings, design ventilation systems that result in an air change effectiveness greater than or equal to 0.9 as determined by ASHRAE 129-1997.

For naturally ventilated spaces demonstrate a distribution and laminar flow pattern that involves not less than 90% of the room or zone area in the direction of airflow for at least 95% of hours of occupancy.”

For mechanically ventilated spaces this credit can be achieved through good diffuser design or by increasing airflow rates. An air change effectiveness of 0.9 means that air movement occurs in 90% of the space. The diffusers should be designed such that air movement occurs throughout the entire space. For naturally ventilated spaces LEED requires CFD or nodal airflow simulations to show compliance. These simulations can be difficult and unreliable. Buildings that incorporate natural ventilation design but have full mechanical ventilation systems can show compliance with this credit through the mechanical system.

The most recent version of LEED USA (v2.2, 2005) has new requirements for this credit. Mechanically ventilated spaces must have outdoor ventilation rates 30% above ASHRAE 62. This can only be achieved by providing a bigger ventilation system (more airflow). Naturally ventilated spaces must have models to show that natural airflows will provide the minimum ventilation rates required by ASHRAE 62 for 90% of occupied spaces. Alternatively, naturally ventilated spaces can be designed according to the Chartered Institution of Building Services Engineers (CIBSE) Applications Manual 10: 2005, Natural ventilation in non-domestic buildings.

5.2.7 Summary of Applicable Standards

A number of standards provide requirements for naturally ventilated buildings. Table 5-3 provides a summary of these standards, discussed in previous sections.

Table 5-3: Summary of standards relating to natural ventilation.

Standard	Natural Ventilation Topics
ASHRAE 55	Acceptable temperature ranges for natural and mechanically ventilated spaces
ASHRAE 62	Airflow rates for mechanically ventilated spaces, opening areas for naturally ventilated spaces
ASHRAE 90	Energy requirements, when energy recovery is required, minimum fan efficiencies
OBC, NBCC	Fire standards on interconnected floor spaces and fire separation; Airflow rates and opening areas in accordance with ASHRAE 62 Specific airflow rates and opening areas for residential and small buildings.
LEED	Calculations and/or simulations required to get credit for naturally ventilated spaces; LEED US requires 30% above ASHRAE 62 airflow rates

5.3 Calculating Natural Ventilation

Natural ventilation occurs when there is a pressure difference across an opening in the building enclosure. Two mechanisms may contribute to the pressure difference: wind pressure and air density differences due to temperature differences (called stack effect). The total pressure difference across an enclosure is the sum of the wind and stack pressure plus any mechanically-induced pressure:

$$\Delta \boldsymbol{P} = \Delta \boldsymbol{P_w} + \Delta \boldsymbol{P_s} + \Delta \boldsymbol{P_m} \qquad \text{Eq. 5-1}$$

The wind pressure at any surface (elevation) of a building is calculated using the Bernoulli equation, (ASHRAE 2009)

$$\Delta \boldsymbol{P_w} = \boldsymbol{C_p \rho \frac{V^2}{2}} \quad \text{Eq. 5-2}$$

Where ΔP_w = Pressure difference due to wind, Pa

V = wind speed, m/s

ρ = outdoor air density, kg/m^3

C_p = wind surface pressure coefficient

Wind speeds recorded at meteorological stations are typically measured in flat, open terrain at a height of 10 m. For the purpose of wind-induced pressure on a building a corrected velocity is used to account for building height and surrounding terrain exposure.

C_p is the wind pressure coefficient, a dimensional coefficient used to account for the pressure variations that form over the face of a building. C_p is determined by the wind direction relative to the wall and the location on the wall. Pressure coefficients have been determined experimentally for various shapes and sizes of buildings, as discussed in ASHRAE Fundamentals Chapter 16 and 24. One correlation for low-rise, rectangular building is, (ASHRAE 2009)

$$\boldsymbol{C_p(\phi) = \frac{1}{2}\Big\{\left[C_p(1) + C_p(2)\right](cos^2\phi)^{\frac{1}{4}} + \left[C_p(1) - C_p(2)\right](cos\phi)^{\frac{3}{4}} + \left[C_p(3) - C_p(4)\right](sin^2\phi)^2 +}$$

$$\boldsymbol{Cp3 - Cp(4) sin\phi} \qquad \text{Eq. 5-3}$$

Where ϕ = Wind angle measured clockwise from the normal to the wall

$C_p(1)$ = Pressure coefficient when wind is at 0°

$C_p(2)$ = Pressure coefficient when wind is at 180°

$C_p(3)$ = Pressure coefficient when wind is at 90°

$C_p(4)$ = Pressure coefficient when wind is at 270°

Typical values are,

$C_p(1) = 0.6$

$C_p(2) = -0.3$

$C_p(3) = C_p(4) = -0.65$

The stack pressure across the building enclosure at any vertical location is, (ASHRAE 2009)

$$\boldsymbol{\Delta P_{stack} = (\rho_o - \rho_i) g \Delta H = \rho_o g \Delta H \left(\frac{T_o - T_i}{T_i}\right)} \qquad \text{Eq. 5-4}$$

Where ΔP_{stack} = Pressure difference due to stack effect, Pa

ΔH = vertical distance from inlet to outlet, m

ρ_o = outdoor air density, kg/m^3

ρ_i = indoor air density, kg/m^3

T_o = outdoor air temperature, K

T_i = indoor air temperature, K

Wind and stack pressure difference across an opening in the enclosure are summed to determine the total natural airflow rate through an opening. The airflow rate, $\dot{Q}$, is equal to, (ASHRAE 2009)

$$\dot{Q} = C_D A \sqrt{\frac{2\,\Delta P}{\rho}} \qquad \text{Eq. 5-5}$$

Where C_D = discharge coefficient for the opening

A = opening area, m^2

ρ = outside air density, kg/m^3

The discharge coefficient depends on the geometry of the opening and the Reynolds number of the flow. An approximate discharge coefficient of $C_D = 0.65$ is recommended by ASHRAE for openings with flow in one direction (either in or out of the opening). For vents designed to provide airflow through enclosures, this value may be provided by the manufacturer based on experimental test data.

5.4 Natural Ventilation Modeling Programs

There are a number of software programs available to assist in the design and calculation of natural ventilation systems. Three available programs that model airflow through a building are CONTAM, LoopDA, and NatVent. These programs are useful for designing natural ventilation systems and evaluating how much airflow is available, however they do not calculate energy consumption of buildings that make use of natural ventilation. Some whole-building energy modeling programs have natural ventilation models that may quantify energy savings from natural ventilation. Programs that model natural ventilation will be discussed here to examine their capabilities, strengths and weaknesses.

5.4.1 CONTAM

CONTAM (Walton 2006) is a software program designed to model airflow through a multi-zone building. This program calculates airflows between zones at the macroscopic level, but does not perform computational fluid dynamic calculations to model airflow within zones. This program models airflow rates and pressure differentials between zones in a building, including the effects of infiltration, exfiltration, airflow due to mechanical systems, wind pressures, and stack effect pressures. The program also has the capability of modeling the movement of contaminants within a building.

The CONTAM program is very easy to use. This program has a graphical user interface that allows users to draw the building as a set of components such as air leakage paths (windows, doors, cracks), ventilation system components (fans, ducts, vents), and contaminant sources. Once the schematic drawing has been created, users define all components by entering parameters for each element. When the simulation is run, CONTAM creates a series of equations from the schematic and calculates the airflow and pressure difference at each flow element. Figure 5-4 (Walton 2006) shows a sample screenshot of the schematic drawing after simulation in CONTAM. The simulation results graphically show airflow rates (blue lines) and pressure differences (red lines) at each component.

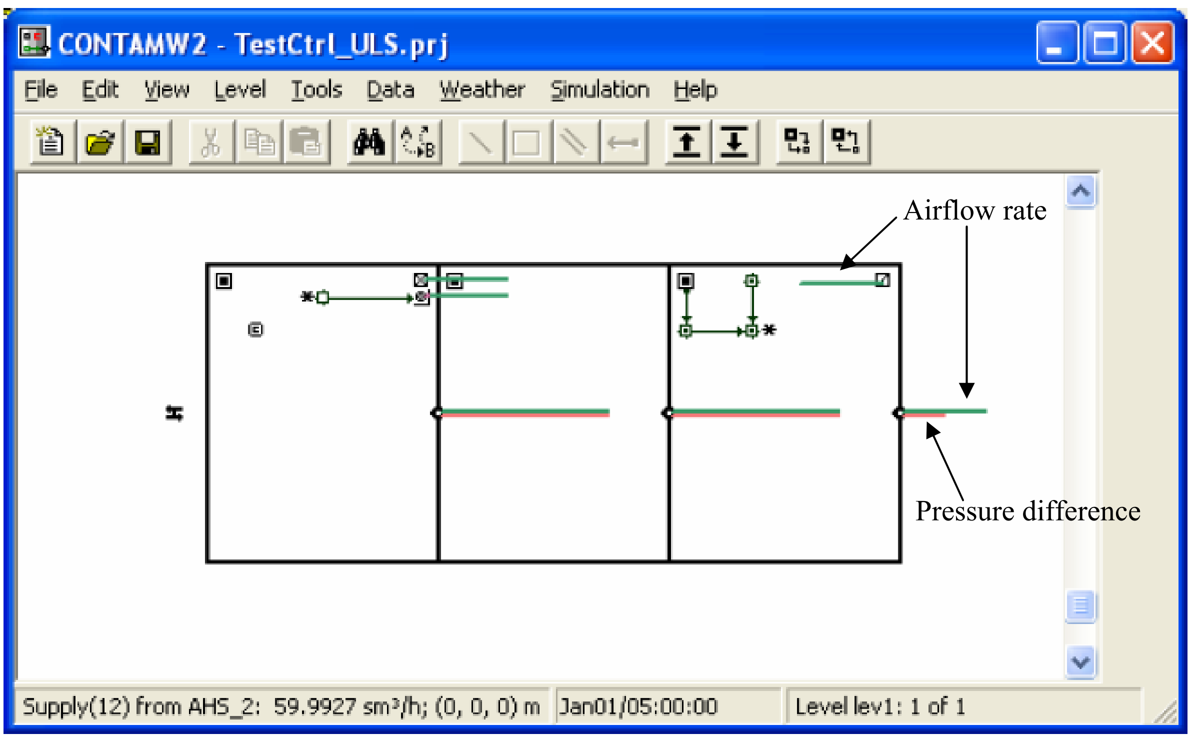


Figure 5-4: Sample CONTAM building schematic and output (Walton 2006).

CONTAM is a useful program for modeling airflow through a building at a high level. It has accurate calculations for modeling a wide range of airflow components, and is quite easy to use. However, CONTAM does not model energy performance of buildings. CONTAM may be used to analyze airflow rates that could be obtained using natural ventilation, but it cannot be used to examine potential energy savings from natural ventilation.

5.4.2 LoopDA

LoopDA (Dols 2003) builds off the CONTAM program to allow users to determine minimum sizes required for natural ventilation openings. This program uses the “Loop Equation Design Method” for calculating natural ventilation airflows. In this method, a natural ventilation flow path or “loop” is designed for each zone. Each loop consists of a series of components, for example fans, window openings, doors, cracks, interior openings, and so on. Design conditions are established (weather, interior temperature and wind pressure coefficients). The objective ventilation rate for each zone is established. The calculation is performed by traversing each airflow loop and solving for the pressure difference and resulting airflow rate at each component. Figure 5-5 (Dols 2003) shows a sample building elevation schematic drawn in LoopDA, with four loops. There is one loop per zone, where each zone is one floor of the building. Figure 5-6 (Dols 2003) shows the simulation results for this example, where blue lines show airflow rates and red lines show pressure differences across airflow components.

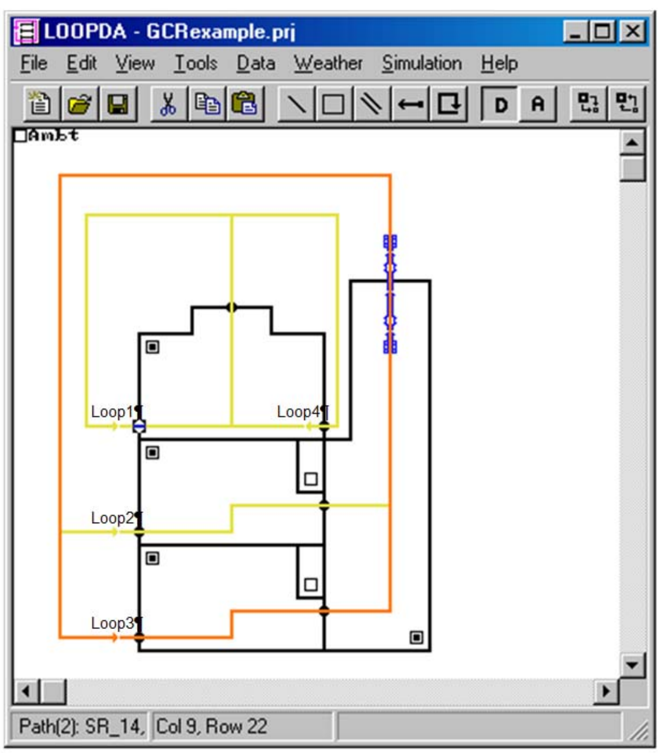


Figure 5-5: Sample LoopDA elevation schematic showing natural ventilation loops (Dols 2003).

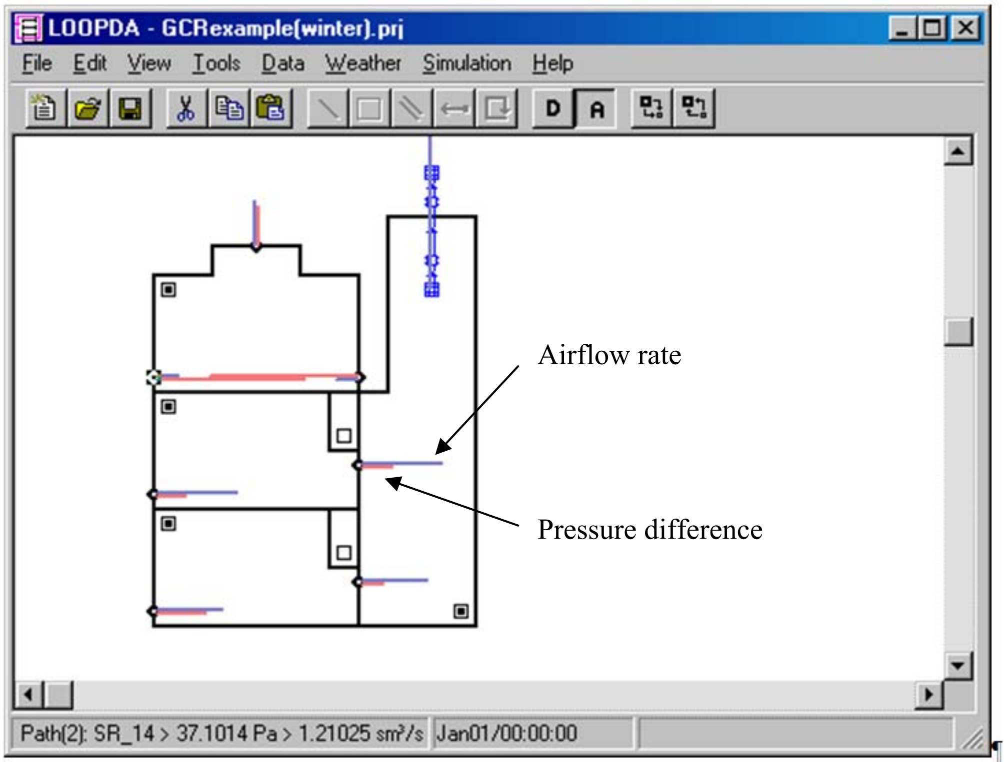


Figure 5-6: Sample LoopDA simulation results (Dols 2003).

The LoopDA program is simple and easy to use, and very useful for determining minimum opening sizes once design criteria for a naturally ventilated building are known. As with CONTAM, this program does not calculate energy consumption of natural ventilation systems. The program only allows sizing calculations to be performed at a single set of design conditions, it does not simulate when natural ventilation does and does not meet minimum ventilation rates.

5.4.3 NatVent

NatVent (Svensson 1998; Svensson and Aggerholm 1998) is a simple program that calculates natural ventilation airflow rates for a single zone building. The program inputs are quite similar to the program developed in this project. Users define a building through four input screens: location, building, ventilation strategy and windows. A sample input screen is shown in Figure 5-7 (Svensson 1998). The NatVent inputs are simple parameters that would be known in the early design stages of a building. NatVent outputs the ventilation rate and indoor temperature at each hour, the number of hours outside a desired temperature range, and plots of percent of work hours versus airflow rate and indoor temperature. The program performs a mass balance at each one-hour time step and iteratively calculates the pressure difference across the building enclosure. The program can then determine airflow rates to the building.

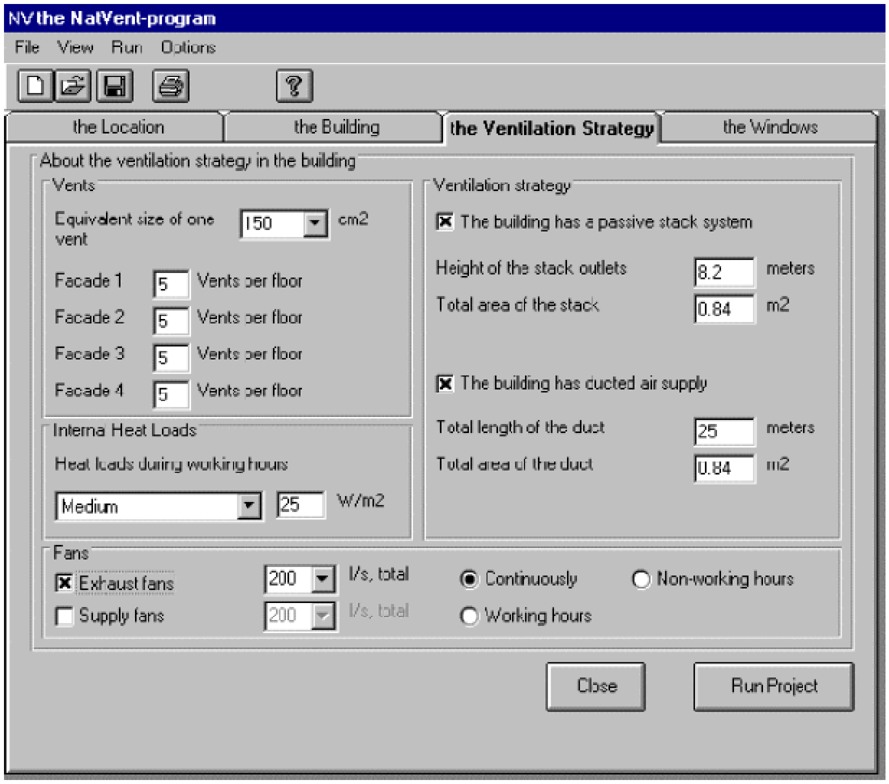


Figure 5-7: Sample input screen for NatVent (Svensson 1998).

This simple program is very useful for determining the feasibility of using natural ventilation for a building as it allows users to view how much airflow is available to ventilate a space. The program has simple inputs and could be used by an architect in early design stages. However, the program does not perform energy calculations and therefore does not give feedback on energy consumption of the natural ventilation system. The program is also limited in that it only models a single-zone.

5.4.4 Whole Building Energy Modeling Programs

Some whole building energy modeling programs include models for natural ventilation, while other programs have commonly accepted workarounds to model natural ventilation. eQuest is one of the most popular and easy to use energy modeling programs. eQuest does not have a model for DOAS or natural ventilation. To model a DOAS system, users must create a dummy zone, define a system for the dummy zone and ventilate all other spaces from the "dummy" system. To model natural ventilation in eQuest, one could modify infiltration schedules to force more outdoor air to enter the building at certain hours of the day. Another method is to force the economizer to 100% with zero fan power for hours when natural ventilation is desired. Neither of these methods allow the program to automatically use natural ventilation when outdoor weather is comfortable.

TRNSYS (University of Wisconsin-Madison Solar Energy Laboratory 2006) includes a simple natural ventilation model. Users must manually define the natural ventilation rate, as seen in the sample window in Figure 5-8. This allows users to simulate potential energy savings from natural ventilation, but with low accuracy. Users cannot view how many hours natural ventilation can meet the building ventilation needs.

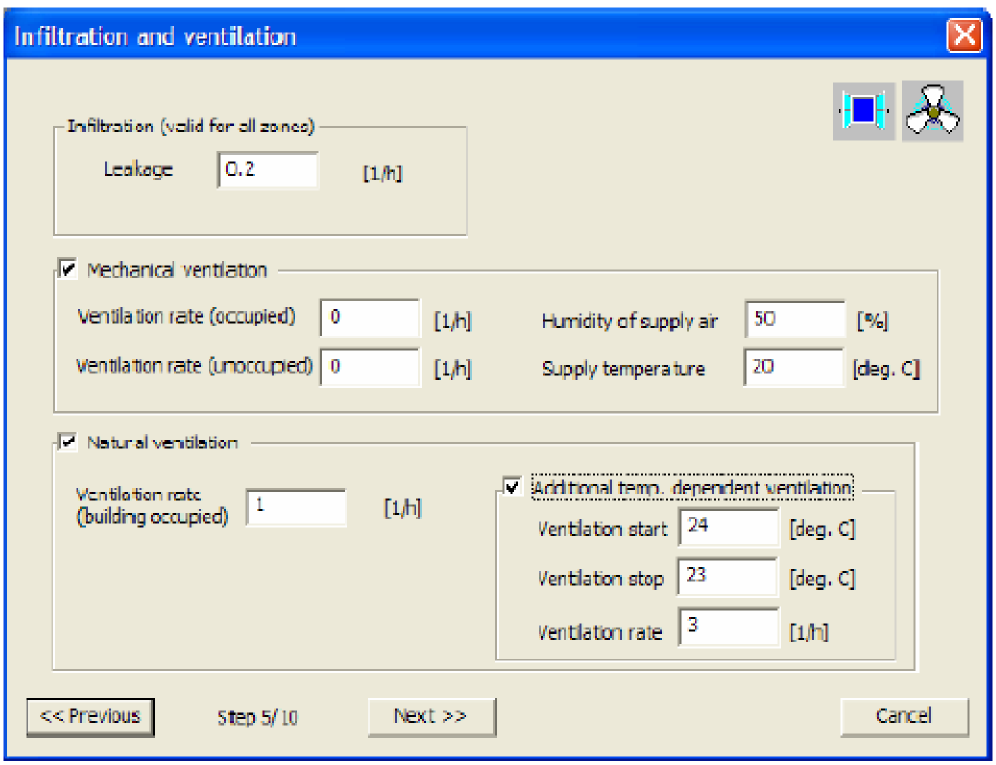


Figure 5-8: TRNSYS screenshot of natural ventilation data entry (University of Wisconsin-Madison Solar Energy Laboratory 2006).

ESP-r (University of Strathclyde Energy Systems Research Unit 2002) has a good natural ventilation model that uses weather data to calculate airflow rates. The model allows users to define an airflow path through a series of components such as doors, windows, and vents. Users can define an outdoor air temperature at which to allow natural ventilation. The simulation can display ventilation rates and incorporate potential energy savings. ESP-r can also simulate air flow within a zone using computational fluid dynamics (CFD).

SUNREL includes a simple natural ventilation model where users can enter the size and location of exterior vents, as well as a minimum outdoor temperature at which natural ventilation is used.

The natural ventilation model to be developed for the spreadsheet-based program will use basic physics to calculate airflow rates, like the program NatVent. Like ESP-r and TRNSYS, the program will tie natural ventilation calculations into the mechanical HVAC system to analyze energy consumption of various configurations.

Chapter 6
Case Study: Natural Ventilation of an Office Building

As discussed in Chapter 5, it is difficult to quantify energy savings from natural and hybrid ventilation systems with the current software programs that are available. The energy modeling program developed in this project can be used for this purpose by adding a natural/hybrid ventilation system model. This will allow the analysis of natural and hybrid ventilation systems with regards to energy consumption.

6.1 Natural and Hybrid Ventilation Model

A natural and hybrid ventilation model was created based on plans for an office building located in Waterloo, Ontario. Floor plans for this building are provided in Appendix A. The building is a two-storey rectangular office building with the long axis facing North-South. Office space is primarily located around the perimeter with locker rooms, washrooms and some meeting rooms in the core of the building. An open, two-storey atrium runs along the long (East-West) axis through the centre of the building with operable windows at the top of the atrium to promote natural ventilation. All perimeter spaces have operable windows and can be naturally ventilated when possible. Spaces that will always require mechanical ventilation include washrooms, locker rooms, interior meeting rooms and janitor rooms.

The goal of this simulation is to analyze the use of natural or hybrid ventilation to ventilate or condition this building with regards to energy consumption. Natural ventilation strategies and air flow paths are examined, and calculations are completed to quantify potential energy savings for this scenario.

6.1.1 Natural Ventilation Strategy

Any number of natural ventilation strategies could be devised for this building. Without changing the floor plan or creating additional elements, the central atrium and clerestory window plan lends itself well to a simple strategy where air enters through the windows at all elevations and exits through the clerestory windows via stack effect. Stack ventilation is driven by temperature differences between the outside and inside, and between the lower and upper volumes of air. Cold air from outside enters at the natural ventilation openings (such as windows or vents), is heated causing it to rise through the building and is exhausted out an upper opening such as clerestory windows. In the summer, when outdoor temperatures are warmer than indoor temperatures, this effect operates in reverse. This strategy is illustrated in Figure 6-1.

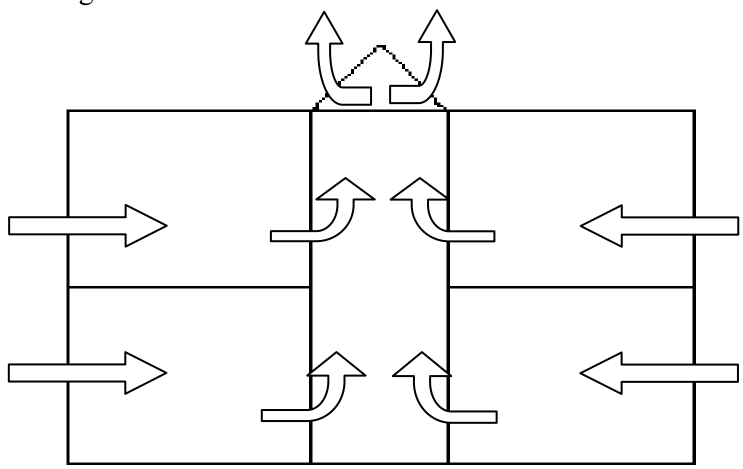


Figure 6-1: Building section showing natural ventilation airflow path.

It is simple to see how outdoor air enters the building through openings such as perimeter windows or vents. However, it is also important to design a clear airflow path inside the building so that air can travel through the space, to the atrium and be exhausted at the roof. This requires elements such as transfer grilles, which create additional resistance to the flow of air that must be accounted for when performing the natural ventilation calculations.

Wind also drives natural ventilation, though this force is much more difficult to predict than stack effect. While stack pressure differences are equal at all elevations (they differ vertically through the building, that is, at each storey), wind forces create positive pressures at the windward elevations and negative pressures at the leeward elevations. Air therefore enters the building at windward elevations, however it can be difficult to predict the airflow path through the building and thus where air exits the building. In this particular building plan, if the negative pressure at the clerestory opening is greater than the negative pressure at the leeward side, air will exit through the clerestory while spaces at the leeward sides may not receive any ventilation. If the opposite is true, the leeward pressure is greater than the clerestory pressure, air will exit through the leeward side rather than the clerestory. These scenarios are illustrated in Figure 6-2. Due to the complexity of the wind calculation, stack ventilation will only be considered in this case study. Analysis of wind effects should be included in future work.

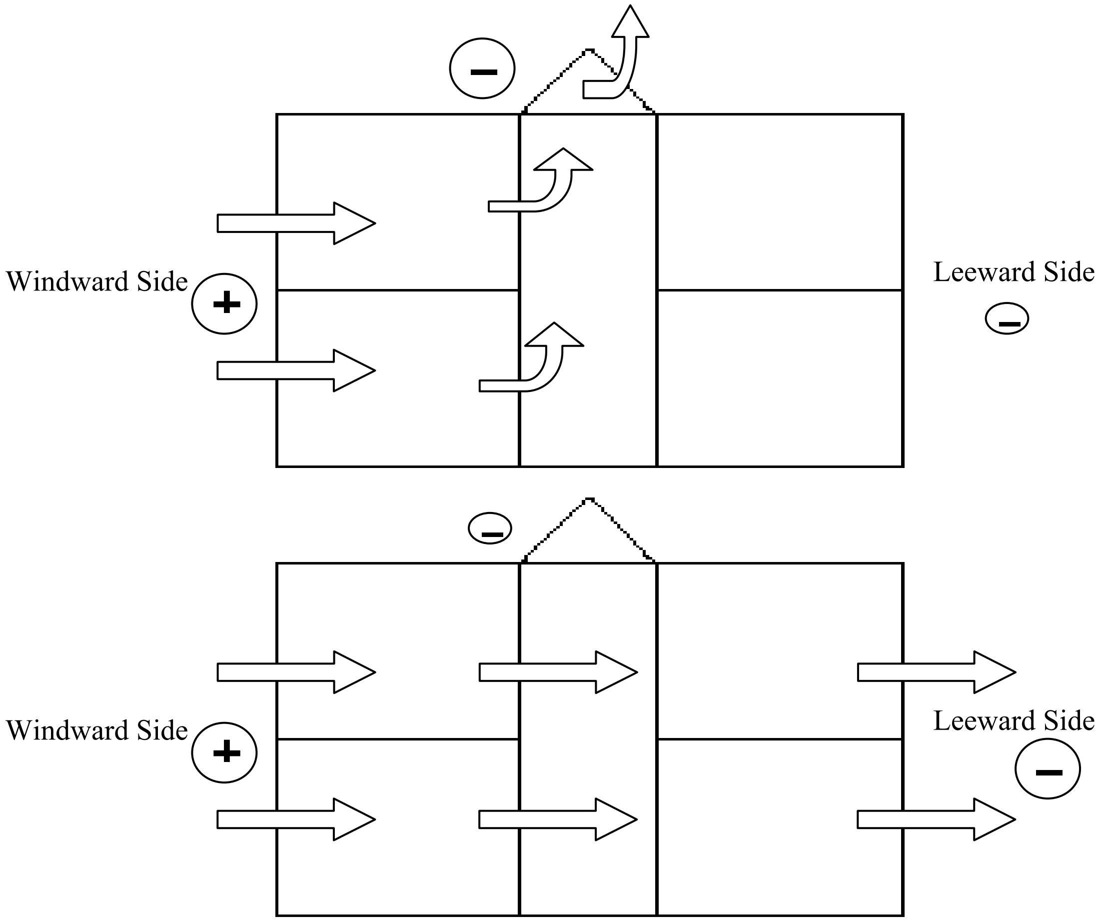


Figure 6-2: Building sections showing possible wind ventilation paths.

6.1.2 Calculation Procedure

The natural ventilation model first calculates the pressure difference across a 1 m^2 opening, and the resulting airflow rate through that opening at each hour of the year. This is done twice, once for a first floor opening and once for a second floor opening. It is assumed that openings have been designed such that the neutral pressure level is located at the dropped ceiling of the second floor. The pressure difference and airflow through an opening due to stack effect are,

$$\Delta P_{stack} = (\rho_o - \rho_i) g \Delta H \qquad \text{Eq. 6-1}$$

$$\dot{Q} = C_D A \sqrt{\frac{2\,\Delta P}{\rho}} \qquad \text{Eq. 6-2}$$

Where ΔH = vertical distance from inlet to outlet, m

ρ_o = outdoor air density, kg/m^3

ρ_i = indoor air density, kg/m^3

C_D = discharge coefficient of opening

A = opening area, m^2

ρ = outside air density, kg/m^3

The program has one sheet with takeoffs that show the percentage breakdown of space by occupancy type and perimeter/core zones. The minimum ventilation rate required for each space is determined from the ASHRAE Standard 62.1-2007, and the amount of natural airflow available at each hour is calculated. The program determines whether mechanical ventilation is required at each hour, and if so the fan power consumed for that hour. Values are summed to determine the total mechanical ventilation energy required over one year.

6.1.3 Building Description and Inputs

Plans for an office building located in Waterloo, Ontario were used as the basis for the natural ventilation model. The building is two stories, rectangular shaped with the long axis facing North-South. The building area is primarily private offices, open office space, and meeting rooms. Other space types include storage rooms, IT rooms, locker rooms, washrooms, lunch room, lobby and corridor. Occupied spaces are located primarily around the perimeter of the building with a central corridor along the East-West axis that is open to the two stories. Most of the interior space is unoccupied, though there are a few meeting rooms and private offices that do not have access to exterior windows. Floor plans and elevations for the building are provided in Appendix A. The division of occupancy types is shown in Table 6-1.

Figure 6-3 and Figure 6-4 show the areas that can be naturally ventilated, and the areas that require mechanical ventilation. Areas in green and blue are connected to perimeter openings and can be naturally ventilated. Areas in yellow are spaces that require mechanical ventilation regardless of their location in the building, such as washrooms, locker rooms and kitchens. Areas in red are interior spaces that could have been served by natural ventilation had they been located differently but will require mechanical ventilation in the given building plan.

Table 6-1: Percent floor area by occupancy type.

Space Type	First Floor		Second Floor	
	Exterior	Interior	Exterior	Interior
Private Office	4%	0%	3%	2%
Open Office	13%	0%	25%	0%
Meeting Room	6%	2%	2%	2%
Lunch Room	7%	0%	0%	0%
Corridor	0%	6%	0%	6%
Lobby	3%	0%	0%	0%
Restrooms	0%	8%	0%	2%
Mechanical/Electrical	0%	0%	3%	0%
Storage Room	0%	1%	3%	3%

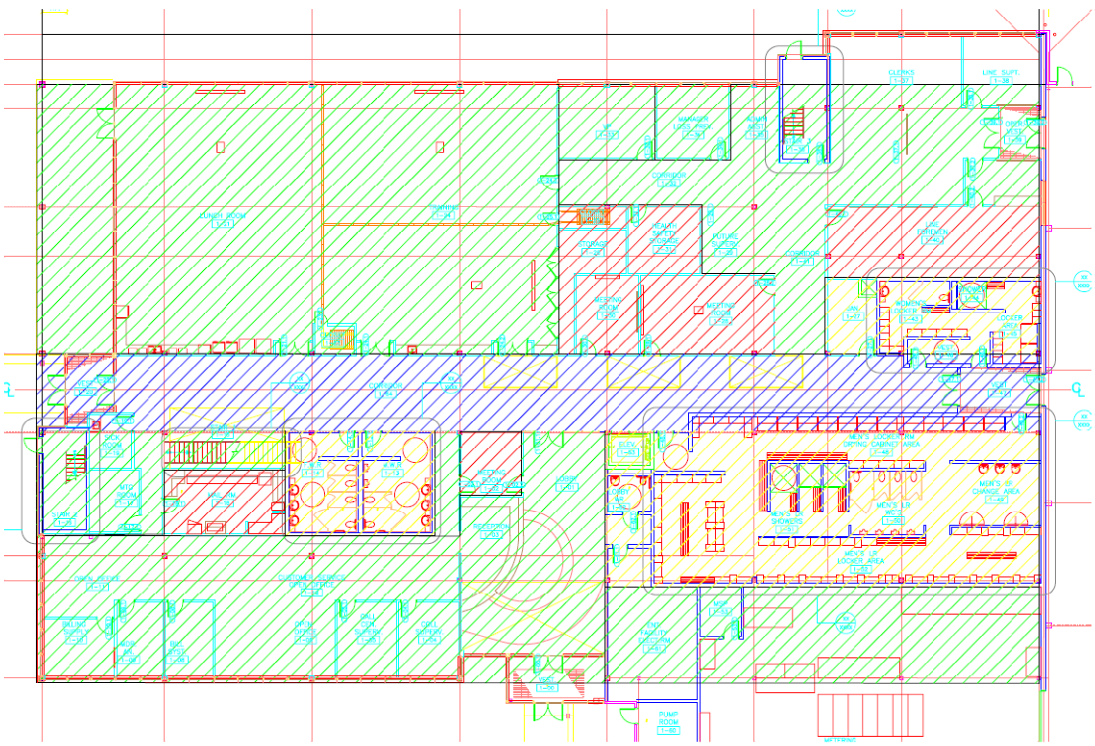


Figure 6-3: First floor ventilation plan.

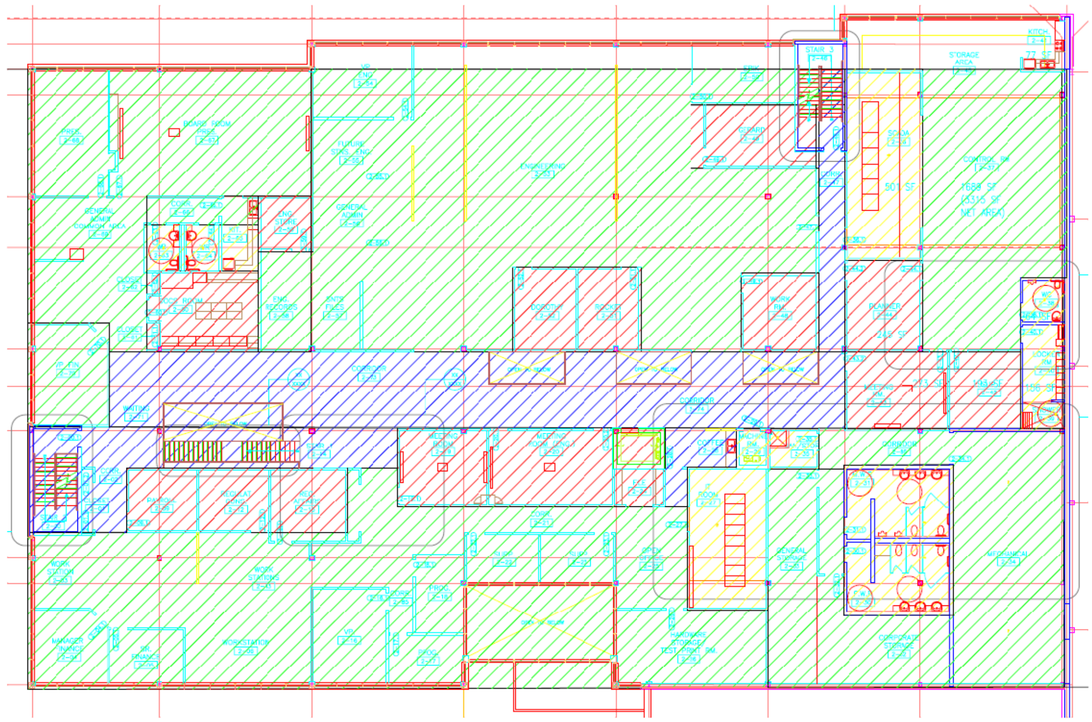


Figure 6-4: Second floor ventilation plan.

Table 6-2 shows a list of inputs used for the natural ventilation model building. Weather for Toronto, Ontario was used since weather data in the appropriate format (CWEC) is not available for Waterloo. Schedules were set up for a typical office building operating five days a week from 8am to 5pm. Occupancy, lights and plug loads are set to 10% of maximum during off hours. Inputs were intended to represent a good, modern office building. For example, the building has good insulation levels, low internal gains, mid to high efficiency mechanical equipment, and so on.

The ventilation rates required for this building are determined from ASHRAE Standard 62.1. All regularly occupied areas of the building require 0.3 l/s per m^2 of floor area plus 2.5 l/s per person. Areas that are not regularly occupied such as storage space, corridors, IT rooms and mechanical rooms require 0.3 l/s per m^2 of floor area. These and other mechanical inputs are shown in Table 6-3.

Table 6-2: List of inputs for natural ventilation model.

General	**Parameter**
Location	Toronto, ON
Number of Stories	2
Length, N-S	61 m
Length, E-W	36 m
Floor to Floor Height	3.7 m
Indoor Temperature, Winter Low	21°C
Indoor Temperature, Summer High	24°C
Enclosure	
Wall R-Value	4.4 m^2-K/W (25 hr-ft^2-F/Btu)
Wall Solar Absorptance	0.8
Roof R-Value	7.0 m^2-K/W (40 hr-ft^2-F/Btu)
Roof Solar Absorptance	0.8
Foundation R-Value	1.8 m^2-K/W (10 hr-ft^2-F/Btu)
Total Window U-Value	1.97 W/m^2-K (0.347 Btu/hr-ft^2-F)
Window Solar Heat Gain Coefficient	0.4
Window to Wall Ratio	30%
Doors	5 doors, 2.1 m x 1.8 m (7 ft x 6 ft)
Infiltration Rate	0.4 l/s-m^2 wall at natural pressure
Internal Gains	
Occupants – Sensible	73 W/person
Occupants – Latent	62 W/person
Occupant Density	7 people per 100 m^2
Lights	8.3 W/m^2 (0.8 W/ft^2)
Plug Loads	12.5 W/m^2 (1.2 W/ft^2)

Operable window areas calculated from the building drawings are shown in Table 6-4 and natural ventilation inputs are shown in Table 6-5. The type of exterior opening and the airflow path through the building are two important design variables. When airflow through an opening is unidirectional, as is the case in the stack ventilation model developed, ASHRAE Fundamentals (16.13) recommends a discharge coefficient of 0.65 for exterior openings (that is, air flows either in or out of an opening). If vents are used instead of windows, the coefficient should be determined from manufacturers' data. For example, Colt "Coltlite" glass louvred ventilators have discharge coefficients around 0.55 (Colt International Ltd. 2008). Vents could also be used that alter the flow rate based on how much airflow is desired.

Table 6-3: Mechanical inputs for case study model.

Mechanical Ventilation	**Parameter**	**Source**
Ventilation Rate – People	2.5 l/s-person	ASHRAE 62.1-2007
Ventilation Rate – Floor Area	0.3 l/s-m^2	ASHRAE 62.1-2007
Minimum Ventilation Rate	0.1 l/s-m^2	
HRV Efficiency	0.7	G3.1.2.10 Minimum 50% heat recovery efficiency
ERV Efficiency	0.7	
Fan Efficiency	60%	
Motor Efficiency	85%	Trane fan catalogue
Design Fan Flow Rate	2500	Total ventilation rate for building including 20% safety factor
Maximum Fan Power	2.6 kW	Using ASHRAE 90.1-2004 Appendix G Section G3.1.2.9
Heating and Cooling		
Heating Efficiency	85%	
Cooling Efficiency	3.5	

Internal resistance is dependent on the transfer grilles used in the building. This value can be determined from manufacturers' data on a particular product. Transfer grilles can be specified to allow higher or lower airflow depending on what is desired. A number of manufacturers' products were examined (Ruskin, Control Aer) to determine an appropriate value for use in this model. A value of 0.10 was selected based on transfer grills that allow a high amount of airflow at low pressures.

Table 6-4: Operable window area by occupancy type.

Space Type	**First Floor [m2]**	**Second Floor [m2]**
Private Office	6.2	9.0
Open Office	15.2	15.2
Meeting Room	5.2	2.4
Lunch Room	4.7	0
Corridor	0	0
Lobby	1.9	0
Restrooms	0	0
Mechanical/Electrical	0	2.4
Storage Room	0	5.2

Table 6-5: Natural ventilation inputs for case study model.

Natural Ventilation	Parameter	Source
Window Discharge Coefficient, C_D	0.65	ASHRAE Fundamentals 16.13
Stack ΔH	1st Floor = 10.8 m 2nd Floor = 6.2 m	Building drawings
Internal Resistance	0.10	Manufacturers' data for interior transfer grilles

6.2 Analysis

6.2.1 Dedicated Outdoor Air System

The natural ventilation analysis will be compared to a Dedicated Outdoor Air System (DOAS). The DOAS energy model is explained in Section 4.3. The DOAS system was chosen for comparison since it is one of the most common, energy-efficient mechanical ventilation strategies used today. Another popular system, Variable Air Volume (VAV) ventilation, was not chosen for this study because it is an inefficient system and may not provide the required ventilation airflows (as discussed in Section 4.1). A highly-efficient system such as natural or hybrid ventilation should be compared to the next best system, an efficient mechanical system.

The model building with a DOAS system uses 161 kWh/m^2, which would be considered to be a good energy intensity for a modern office building. For comparison, the average energy intensity of commercial office buildings in Canada in 2005 was 444 kWh/m^2 (NRCan 2004). Ultra-low energy office buildings can be realized, for example the office of Enermodal Engineering Ltd. in Kitchener, Ontario is projected to use 65 kWh/m^2 (Enermodal 2010).

Figure 6-5 shows the annual energy consumption for this building. It can be seen that ventilation energy accounts for 8% of total energy consumption, and space cooling is an additional 12%. The maximum possible energy savings from natural ventilation due to fan power and free cooling savings is 20% of the total building energy.

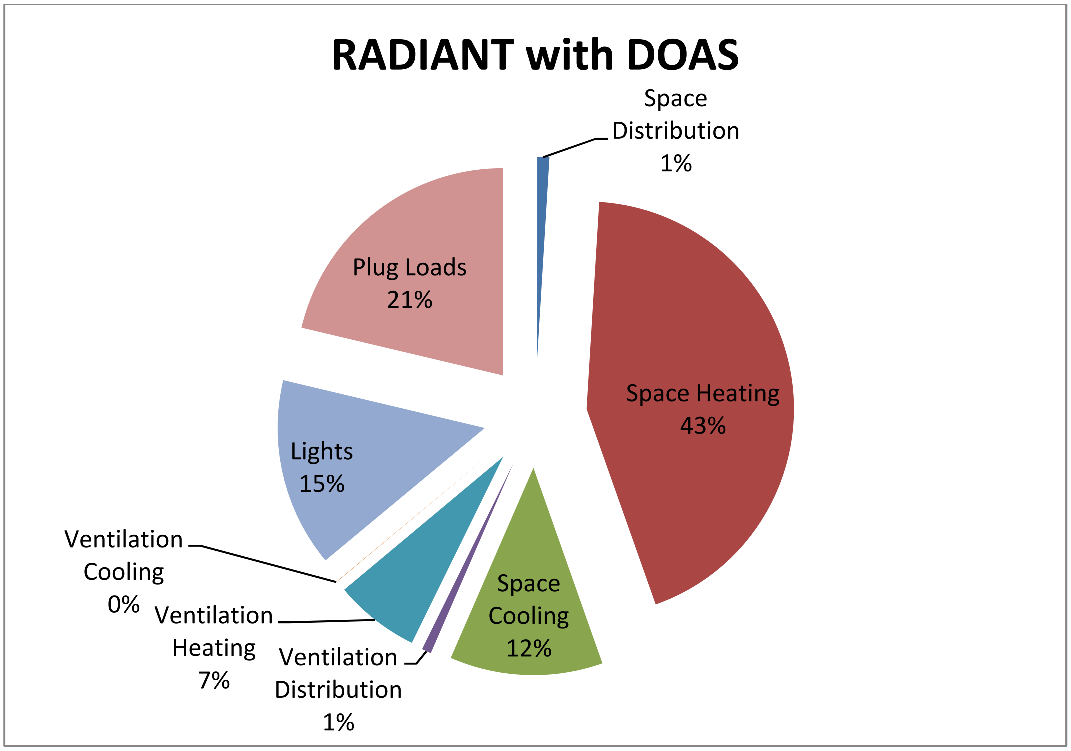


Figure 6-5: Energy consumption for model building with DOAS ventilation.

6.2.2 Natural Ventilation All Hours, Windows Fully Open

To begin this study it is assumed that natural ventilation is used during all hours of the year, regardless of the outdoor weather. It should be expected that fan power will be significantly lower, while heating energy will be higher due to the added heating load from letting cold air into the building. In reality this scenario presents comfort problems in a cold climate due to cold air drafts and the possibility of too much airflow. However, it will be used as a starting point in this study to analyze all options.

In this scenario, natural ventilation can meet the building ventilation requirements 98.2% of the hours in the year, leaving 156 hours where there is not enough airflow. These hours are mostly sporadic and so would not be a problem, with the exception of nine days where there is not enough ventilation for four to eight consecutive hours.

For most hours of the year, far more airflow enters the building than is required by ASHRAE Standard 62.1. For example, on a winter day when 219 l/s of ventilation air is required for the first floor open office space, about 5000 l/s of air enters this area. This imposes an additional higher than necessary load on the space heating and cooling systems.

Table 6-6 shows the annual energy consumption for this scenario. As expected, space heating energy is extremely high as a large amount of cold air is entering the building. Space cooling energy is lower in the winter due to the savings from free cooling, but higher in the summer due to the large amount of hot, humid air entering the building. Over the course of a year, space cooling energy is reduced by 10 kWh/m^2 due to the savings from free cooling. The fan power required in this scenario is for spaces that still require mechanical ventilation such as washrooms and locker rooms. Fan power ("ventilation distribution") is much lower than with a DOAS, though savings are negligible compared to the extremely large increase in space heating. Plots showing monthly energy consumption for these significant areas are provided in Appendix B.

Table 6-6: Results for Natural Ventilation all hours, windows fully open.

	DOAS {kWh/m^2}	**NV All Hours, Windows Open {kWh/m^2}**
Space Distribution	1.6	1.6
Space Heating	70.2	736.7
Space Cooling	19.2	9.2
Ventilation Distribution	1.2	0.1
Ventilation Heating	10.7	2.1
Ventilation Cooling	0.05	0.0
Lights	23.7	23.7
Plug Loads	34.3	34.3
TOTAL	160.9	807.6

6.2.3 Natural Ventilation All Hours, Windows Optimally Open

The scenario where windows are fully open to naturally ventilate the building at all times created large natural airflows. Windows could be fitted with automated actuators to optimally control airflow such that only the amount required enters the building. Alternatively, vents or dampers could be used to obtain the same effect. The effect of optimally controlling ventilation openings to provide only the amount of ventilation required is now examined.

Table 6-7 shows the annual energy consumption for this scenario. Heating energy is less than 11% of the scenario with windows fully open, though it is still higher than the DOAS. As before, space cooling energy is slightly higher in summer months and lower in winter months due to the gains from free cooling. Over the course of a year, however, the gains in free cooling are smaller in this scenario than when windows are fully open as less free cooling is available. The window control scheme could be further optimized to maximize free cooling when cooling is required. Fan energy ("Ventilation Distribution") is identical in the two scenarios. It should also be noted that the reduction in "Ventilation Heating", 8.6 kWh/m^2, is close to the increase in "Space Heating", 9.6 kWh/m^2; the load is essentially moved from ventilation heating to space heating.

Table 6-7: Results for Natural Ventilation all hours, windows optimally open.

	DOAS {kWh/m^2}	NV All Hours, Windows Open {kWh/m^2}	NV All Hours, Windows Optimal {kWh/m^2}
Space Distribution	1.6	1.6	1.6
Space Heating	70.2	736.7	79.8
Space Cooling	19.2	9.2	15.6
Ventilation Distribution	1.2	0.1	0.1
Ventilation Heating	10.7	2.1	2.1
Ventilation Cooling	0.05	0.0	0.0
Lights	23.7	23.7	23.7
Plug Loads	34.3	34.3	34.3
TOTAL	160.9	807.6	157.2

The total building energy consumption in this scenario is 157.2 kWh/m^2, slightly lower than the building energy consumption of the DOAS, 160.9 kWh/m^2. This scenario could create comfort problems due to cold air drafts entering the building.

6.2.4 Comfort Limited Natural Ventilation (Hybrid Ventilation), Windows Fully Open

Natural ventilation could be used only when outdoor weather is good, and outdoor air can be brought into the building without causing occupant discomfort. In this model, natural ventilation is used when outdoor air is warmer than 15 degrees Celsius and less than 85% relative humidity.

In this scenario, natural ventilation can meet building ventilation requirements 21% of the hours in a year. This leaves 6,939 hours where mechanical ventilation is required to achieve minimum ventilation rates. When natural ventilation is used, air flow rates are higher than the minimum rates required. For example, on a June day when 219 l/s of ventilation is required for the first floor open office space, over 1000 l/s can enter the space. This can create an unnecessary heating load if outdoor air is cooler than the design air temperature.

Table 6-8 shows the annual energy consumption for this scenario. Annual energy consumption for space heating is still higher than with a DOAS system due to the added load from the large volume of cool (15°C) air entering the building. Space cooling energy is higher in July and lower in swing months due to savings from free cooling, as shown in Figure 6-6. However, over an entire year, space cooling energy is quite close for DOAS and hybrid ventilation. This means the hybrid ventilation is not taking advantage of free cooling savings when a cooling load is present. Annual fan energy savings are still present, though not as high as when ventilation is used for all hours.

Table 6-8: Results for comfort limited Natural Ventilation, windows fully open.

	DOAS {kWh/m^2}	**HV, Windows Open {kWh/m^2}**
Space Distribution	1.6	1.6
Space Heating	70.2	78.6
Space Cooling	19.2	18.2
Ventilation Distribution	1.2	0.8
Ventilation Heating	10.7	10.2
Ventilation Cooling	0.05	0.0
Lights	23.7	23.7
Plug Loads	34.3	34.3
TOTAL	160.9	167.4

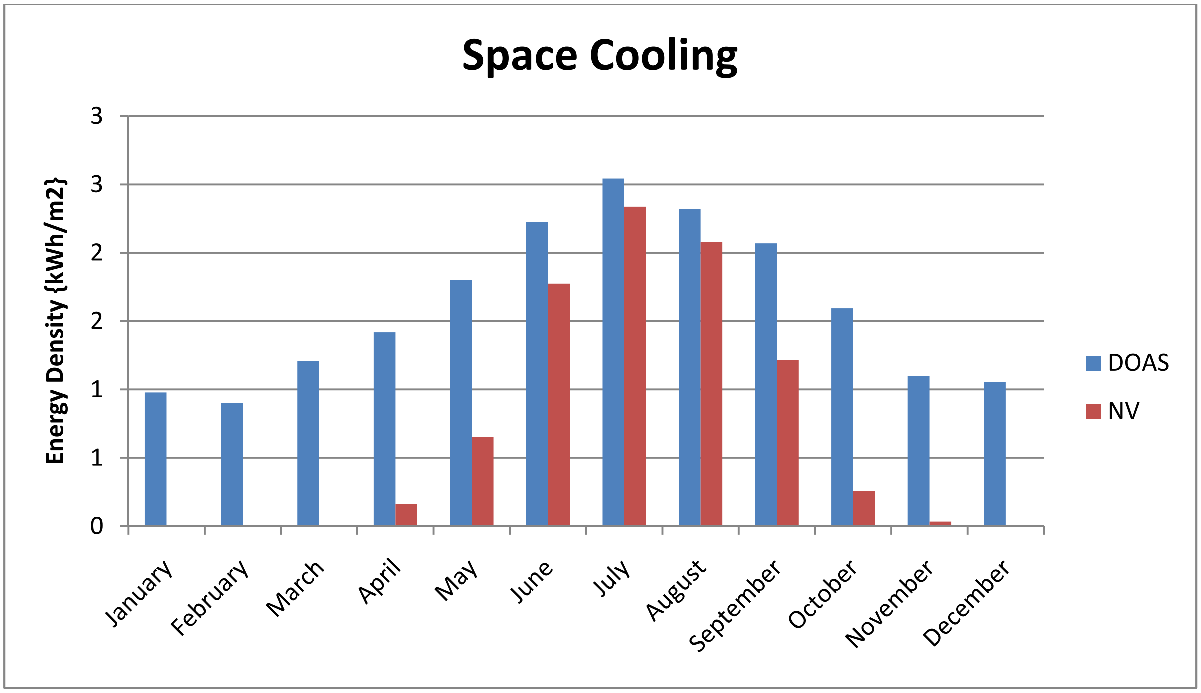


Figure 6-6: Space cooling energy consumption for HV with windows fully open.

Total building energy for this scenario is 167.4 kWh/m^2, higher than energy used with the DOAS system (160.9 kWh/m^2) and the scenario with NV all hours and windows optimally open (157.2 kWh/m^2). This is due to the fact that higher than necessary natural airflow at temperatures that are still below the indoor design temperature create an unnecessary increase in heating load.

6.2.5 Comfort Limited Natural Ventilation (Hybrid Ventilation), Windows Optimally Open

When natural ventilation is used only in good outdoor weather conditions and windows are left fully open, high airflows cause high space heating and cooling loads. Window or vent openings could be controlled automatically to allow only the required ventilation airflow rate.

Table 6-9 shows the energy consumption for one year for this scenario. Compared to the DOAS system, space heating energy is only slightly higher (increase of 0.2 kWh/m^2), space cooling energy is slightly lower (0.2 kWh/m^2) and fan power is lower. The total building energy consumption over the year is slightly lower at 160.0 kWh/m^2 compared to the DOAS value of 160.9 kWh/m^2. Energy savings come from the reduction in fan power and small savings in space cooling. Further energy savings could be realized by optimizing windows to also take advantage of free cooling.

Table 6-9: Results for comfort limited Natural Ventilation, windows optimally open.

	DOAS {kWh/m^2}	HV, Windows Open {kWh/m^2}	HV, Windows Optimal {kWh/m^2}
Space Distribution	1.6	1.6	1.6
Space Heating	70.2	78.6	70.4
Space Cooling	19.2	18.2	19.0
Ventilation Distribution	1.2	0.8	0.8
Ventilation Heating	10.7	10.2	10.2
Ventilation Cooling	0.05	0.0	0.0
Lights	23.7	23.7	23.7
Plug Loads	34.3	34.3	34.3
TOTAL	160.9	167.4	160.0

6.2.6 Comfort Limited Natural Ventilation (Hybrid Ventilation), Windows Optimal, Free Cooling

It has been shown in the previous scenario that hybrid ventilation can save energy in the form of fan power when airflow rates are limited to provide only the required amount to meet ventilation standards. However, further energy reductions could be realized by also controlling outdoor air flow to optimize free cooling. When the building has a cooling load and the outdoor air temperature is lower than the indoor air temperature, windows or vents can be opened to provide the necessary cooling load.

Table 6-10 shows the annual energy consumption for this scenario. Space cooling is lower in every month, as shown in Figure 6-7, and the annual total is reduced from19.2 kWh/m^2 to 8.5 kWh/m^2. Total building energy consumption is down to 149.5 kWh/m^2, compared to 160.9 kWh/m^2 for the DOAS system.

Table 6-10: Results for comfort limited Natural Ventilation, windows optimally open, free cooling.

	DOAS {kWh/m^2}	HV, Windows Open {kWh/m^2}	HV, Windows Optimal {kWh/m^2}	HV, Free Cooling {kWh/m^2}
Space Distribution	1.6	1.6	1.6	1.6
Space Heating	70.2	78.6	70.4	70.4
Space Cooling	19.2	18.2	19.0	8.5
Ventilation Distribution	1.2	0.8	0.8	0.8
Ventilation Heating	10.7	10.2	10.2	10.2
Ventilation Cooling	0.05	0.0	0.0	0.0
Lights	23.7	23.7	23.7	23.7
Plug Loads	34.3	34.3	34.3	34.3
TOTAL	160.9	167.4	160.0	149.5

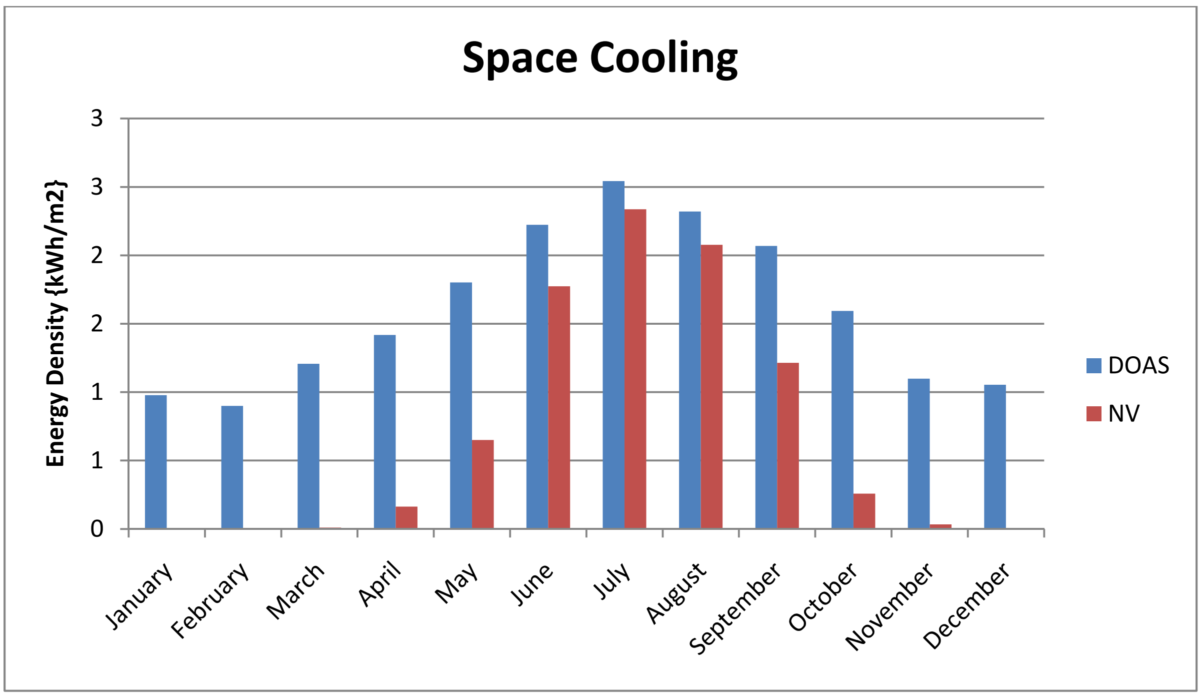


Figure 6-7: Space cooling energy for free cooling scenario.

This scenario reduces total building energy consumption by 11.4 kWh/m^2 per year or 7% compared to a DOAS system, which would save about 50,000 kWh/year. To get a rough idea of dollar savings, an electricity price of $0.09/kWh would result in a savings of $4,500 per year.

The energy savings obtained from natural ventilation in this scenario could be significant, but other energy efficiency measures may result in greater savings. An accurate payback analysis is beyond the scope of this project. However, this scenario would require finely-controlled operable vents or windows, likely at a high initial cost. It may be better to focus efforts on adding insulation, better windows, reducing thermal bridging, more efficient mechanical equipment, and so on. If other energy efficiency measures have been exhausted and further energy savings are desired, natural ventilation would be a good strategy to investigate.

6.3 Summary

A quantitative analysis of the energy consumption of natural and hybrid ventilation compared to DOAS ventilation has been completed for a new office building to be located in Waterloo, Ontario. It is shown that using natural ventilation during all hours of the year, regardless of outdoor weather, consumes more energy due to the increased space heating and cooling load. Using natural ventilation only when outdoor air is such that it will not cause occupant discomfort ("hybrid ventilation") reduces building energy consumption if airflows are limited to provide only the amount of air that is necessary. For the building studied, this reduces annual building energy consumption by 11.4 kWh/m^2 (7%). This reduction is small compared to savings that could be obtained through other energy efficiency measures such as added insulation and better windows, however the reduction could be significant once other energy efficiency measures have been exhausted. Table 6-11 shows a summary of the energy consumption of the various scenarios analyzed.

Table 6-11: Summary natural ventilation systems energy consumption.

	Total Energy {kWh/m^2}	**% Savings vs. DOAS**
DOAS	160.9	-
NV all hours, windows fully open	807.6	+400%
NV all hours, windows optimally open	157.2	-2%
Comfort Limited NV, Windows Fully Open	167.4	+4%
Comfort Limited NV, Windows Optimally Open	160.0	-0.6%
Comfort Limited NV, Windows Optimal, Free Cooling	149.5	-7%

This study could be expanded to investigate numerous other scenarios. The building studied here had low thermal mass; it would be interesting to repeat this study for a building with high thermal mass.

Nighttime precooling in summer months could also be examined for a building with high thermal mass. The same analysis could be completed using a different climate, for example cooling climates like the southern United States or mild climates such as Vancouver, Canada. The analysis could also be completed for different building sizes, shapes, and occupancy types. A cost-payback study could be completed to compare natural ventilation as an energy efficiency measure to other common energy efficiency measures.

Chapter 7
Conclusions and Recommendations

An important part of the design of a low energy building is modeling the building to predict energy consumption and evaluate the energy efficiency measures being considered. While energy modeling is a cost effective tool to assist in design, there are a number of challenges in the current building energy modeling industry. Most energy modeling programs are too technical to be used by architects, and too complex for early design when many system parameters are not known. Programs that are easy to use lack accuracy and the ability to model new, innovative systems. Programs that allow the simulation of new systems are very complex and have a steep learning curve. This thesis has reviewed a number of common energy modeling programs to identify strengths and weaknesses of the modeling tools that are currently available.

A new energy modeling program, Building Energy and Loads Analysis or BELA, was developed to address some of the weaknesses of the existing programs, particularly for the early stages of design. The program models building energy loads and energy consumption of mechanical systems. The program is intended to be easy to use, adaptable to new and innovative systems, and to facilitate simple simulation during early design stages as well as detailed simulation during later design stages.

The BELA program generally consists of two parts: the loads model and the systems model. In the loads model, users define a building through a series of inputs. The program uses these inputs to calculate the total net heat transfer entering a building and heat gains from lights, people and plug loads. This defines the total heating or cooling load on the space. This calculation is conducted at every hour in a year. Heat transfer mechanisms considered include conduction through the walls, windows, doors, roof and foundation, solar heat gain through windows, infiltration, and heat gain from occupants, lights and plug loads. The program uses the transfer function method to account for thermal storage effects in determining the hourly heating or cooling load. The output of the loads model can be used to view the loads on the buildings, and to view how enclosure design parameters such as the amount of insulation or the type of window affect the building loads over an entire year.

The systems model calculates the total energy consumption of the building every hour for a year. Two heating and cooling systems models have been created thus far, radiant heating and cooling, and fan coil units, both with a dedicated outdoor air system (DOAS) to provide ventilation. The output of the systems models shows the total energy consumption of the building for one year. It can be used to compare different mechanical systems and evaluate various design parameters within the systems.

A natural ventilation model was created for the BELA program to demonstrate the implementation of an innovative system and analyze the energy consumption of a natural or hybrid ventilation system. Natural ventilation is challenging to implement in cold climates as allowing too much unconditioned air to enter the building could result in excess loading on the space conditioning system, and could cause occupant discomfort. Many cold-climate buildings that make use of natural ventilation do so only during swing seasons, and have full mechanical ventilation systems for times when outdoor weather is not good. There is often no quantitative design or analysis that goes into naturally ventilated buildings, and therefore it is not know whether these strategies actually reduce energy consumption and by how much.

A case study building model was created to analyze energy consumption of a naturally ventilated building. Plans for a two-story office building located in Waterloo, Ontario were used for the model. Energy consumption of a DOAS was compared to energy consumption of various configurations of natural ventilation.

The case study model showed that natural or hybrid ventilation can reduce building energy consumption when designed properly, however when used incorrectly it can significantly increase energy consumption. For scenarios where opening sizes were not restricted to provide only the necessary airflow, energy consumption of natural ventilation was higher than the DOAS system. This was due to the increased space heating and cooling loads from too much unconditioned air entering the building. When opening sizes were limited to provide only the required airflow rates and to take advantage of free cooling, energy consumption for a year was reduced by 3.5%. This simulation showed that natural ventilation may save a small amount of energy when designed correctly. However, designers should evaluate it alongside other energy efficiency measures that may provide greater energy savings.

Recommendations

It is recommended that future work be completed to continue the development of this program. A number of improvements could be made to the loads and systems model to improve the accuracy of the program. Systems models could be added for a larger number of HVAC systems to facilitate a wide range of simulations. The program as a whole could be adapted to model multiple zones to consider a wider range of buildings.

The natural ventilation analysis could be expanded to analyze different building geometries, buildings in different climates, buildings with different levels of thermal mass, and cost-payback of natural ventilation.

References

ASHRAE. (2009). *ASHRAE Handbook - Fundamentals.* Atlanta: American Society of Heating, Refrigeratingand Air Conditioning Engineers, Inc.

ASHRAE. (2009). *Dedicated Outdoor Air Systems.* Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

ASHRAE. (2004). *Standard 55: Thermal Environmental Conditions for Human Occupancy.* Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

ASHRAE. (2007). *Standard 62.1: Ventilation for Acceptable Indoor Air Quality.* Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

ASHRAE. (2007). *Standard 90: Energy Standard for Buildings.* Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

Brager, G. a. (2000). A Standard for Natural Ventilation. *ASHRAE Journal* .

Bronsema, N. (2009). *Solar Equations.* Waterloo: University of Waterloo.

CaGBC. (2004). *Leadership in Energy and Environmental Design (LEED) v1.0.* Ottawa: Canadian Green Building Council.

Canada. (2005). *National Building Code of Canada.* Ottawa: Government of Canada.

Colt International Ltd. (1998). *Coltlite Natural Glass Louvred Ventilator.* England.

Control Aer Ltd. (2008). *Excelsior Vision-Proof Transfer Grille Type NVF.* Leeds: Control Aer Ltd.

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2005). *Contrasting the Capabilities of Building Energy Performance Simulation Programs.* Washington D.C.: U.S. Department of Energy.

Deru, M. R., Judkoff, R., & Torcellini, P. (2002). *SUNREL Technical Reference Manual.* Golden: National Renewable Energy Laboratory.

DOE. (2006, 10 19). *Building Energy Software Tools Directory*. Retrieved 04 08, 2010, from U.S. Department of Energy: http://apps1.eere.energy.gov/buildings/tools_directory/subjects_sub.cfm

Dols, W. S., & Emmerich, S. J. (2003). *LoopDA - Natural Ventilation Design and Analysis Software.* Gaithersburg: National Institute of Standards and Technology.

Energy Systems Research Unit, University of Strathclyde. (2002). *The ESP-r System for Building Energy Simulation User Guide Version 10 Series.* England: University of Strathclyde.

Enermodal Engineering Ltd. (2009). *A Grander View.* Retrieved 03 21, 2010, from Enermodal Engineering Ltd.: http://www.enermodal.com/Canadian/company_building.html

Harriman, L. G., Brundrett, G. W., & Kittler, R. (2001). *Humidity Control Design Guide for Commercial and Institutional Buildings.* Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

James J. Hirsch & Associates. (2009). *eQuest Introductory Tutorial Version 3.63.* Camarillo: James J. Hirsch & Associates.

Kettler, J. (1995). Minimum Ventilation Control for VAV Systems: Fan Tracking vs. Workable Solutions. *ASHRAE Transactions , 101* (2), 625-630.

LBL. (1982). *DOE-2 Engineers Manual Version 2.1A.* Berkeley: Lawrence Berkeley Laboratory.

LBNL. (2004). *DOE-2.2 Volume 1: Basics.* Berkeley: Lawrence Berkeley National Laboratory.

LBNL. (2009). *EnergyPlus Engineering Reference.* Berkeley: Lawrence Berkeley National Laboratory.

LBNL. (2009). *Getting Started with EnergyPlus.* Berkeley: Lawrence Berkeley National Laboratory.

LBNL. (2003). *NFRC Simulation Manual.* Berkeley: Lawrence Berkeley National Laboratory.

McQuiston, F. C., & Spitler, J. D. (1992). *Cooling and Heating Load Calculation Manal, 2nd Edition.* Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

McQuiston, F. C., Parker, J. D., & Spitler, J. D. (2005). *Heating, Ventilating and Air Conditioning: Analysis and Design, 6th Edition.* Hoboken: John Wiley & Sons, Inc.

Mitalas, G. (1972). Transfer Function Method of Calculating Cooling Loads, heat Extraction and Space Temperature. *ASHRAE Journal , 14* (12), 54-56.

Mumma, S. A., & Lee, B. (1998). Extension of the Multiple Spaces of Concept of ASHRAE Standard 62 to Include Infiltration, Exhaust/Exfiltration, Interzonal Transfer, and Additional Short-Circuit Paths. *ASHRAE Transactions , 104* (2), 1232-1241.

Mumma, S. A., & Wong, Y. M. (1990). Analytical evaluation of outdoor airflow rate variations vs. supply airflow rate variation in Variable-Air-Volume systems when the outdoor air damper position is fixed. *ASHRAE Transactions , 96* (1), 1197-1209.

Mumma, S. (2003). HVAC: The Next Generation. *Consulting-Specifying Engineer* (January), 38-42.

NRCan. (2005). *Commercial and Institutional Consumption of Energy Survey.* Ottawa: Natural Resources Canada.

NRCan. (2008). *EE4 Software Version 1.7 Modeling Guide.* Ottawa: Natural Resources Canada.

NRCan. (2005). *Energy Use Data Handbook.* Ottawa: Natural Resources Canada.

NRCan. (2009, 03 24). *HOT2000.* Retrieved 03 22, 2010, from Natural Resourcecs Canada: http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/software_tools/hot2000.html

NRCan. (2009, 03 24). *HOT3000.* Retrieved 03 22, 2010, from Natural Resources Canada: http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/software_tools/hot3000.html

Olesen, B. (2008). Radiant Floor Cooling Systems. *ASHRAE Journal* (September), 16-22.

Ontario. (2006). *Ontario Building Code.* Toronto: Government of Ontario.

Ruskin Air Management Ltd. (2007). *Narrow Transfer Grille Model NTG.* England.

Solar Energy Laboratory, University of Wisconsin - Madison. (2006). *TRNSYS16 Documentation.* Madison: University of Wisconsin.

Stephenson, D. G., & Mitalas, G. P. (1967). Cooling Load Calculations by Thermal Response Factor Method. *ASHRAE Transactions , 73* (1).

Straube, J. F., & Burnett, E. F. (2005). *Building Science for Building Enclosures.* Westford: Building Science Press Inc.

Svensson, C. (1998). *The NatVent Programme 1.0 User's Guide.* Sweden: J&W Consulting Engineers.

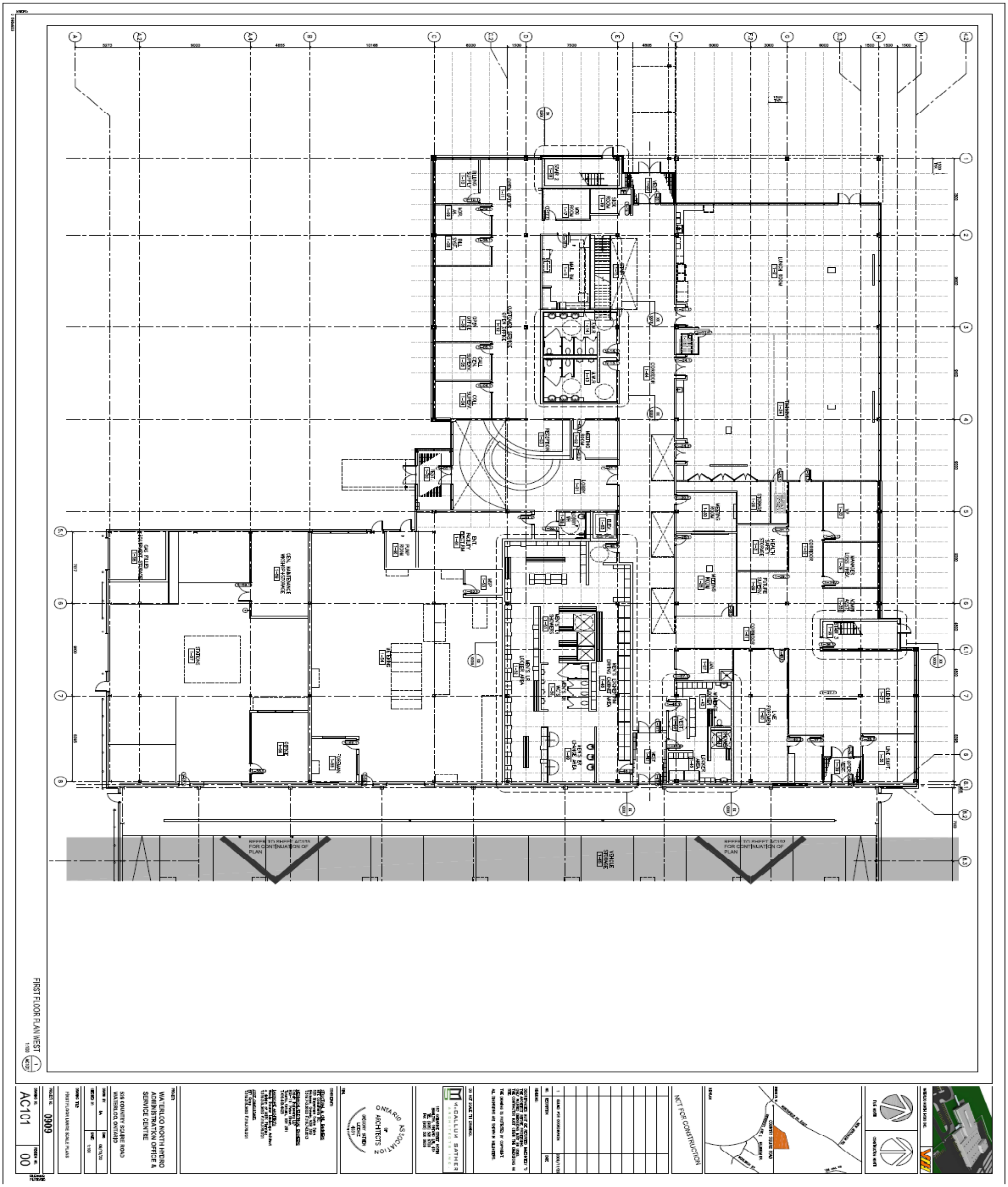
Svensson, C., & Aggerholm, A. (1998). *The NatVent Programme 1.0 Fundamentals.* Sweden: J&W Consulting Engineers.

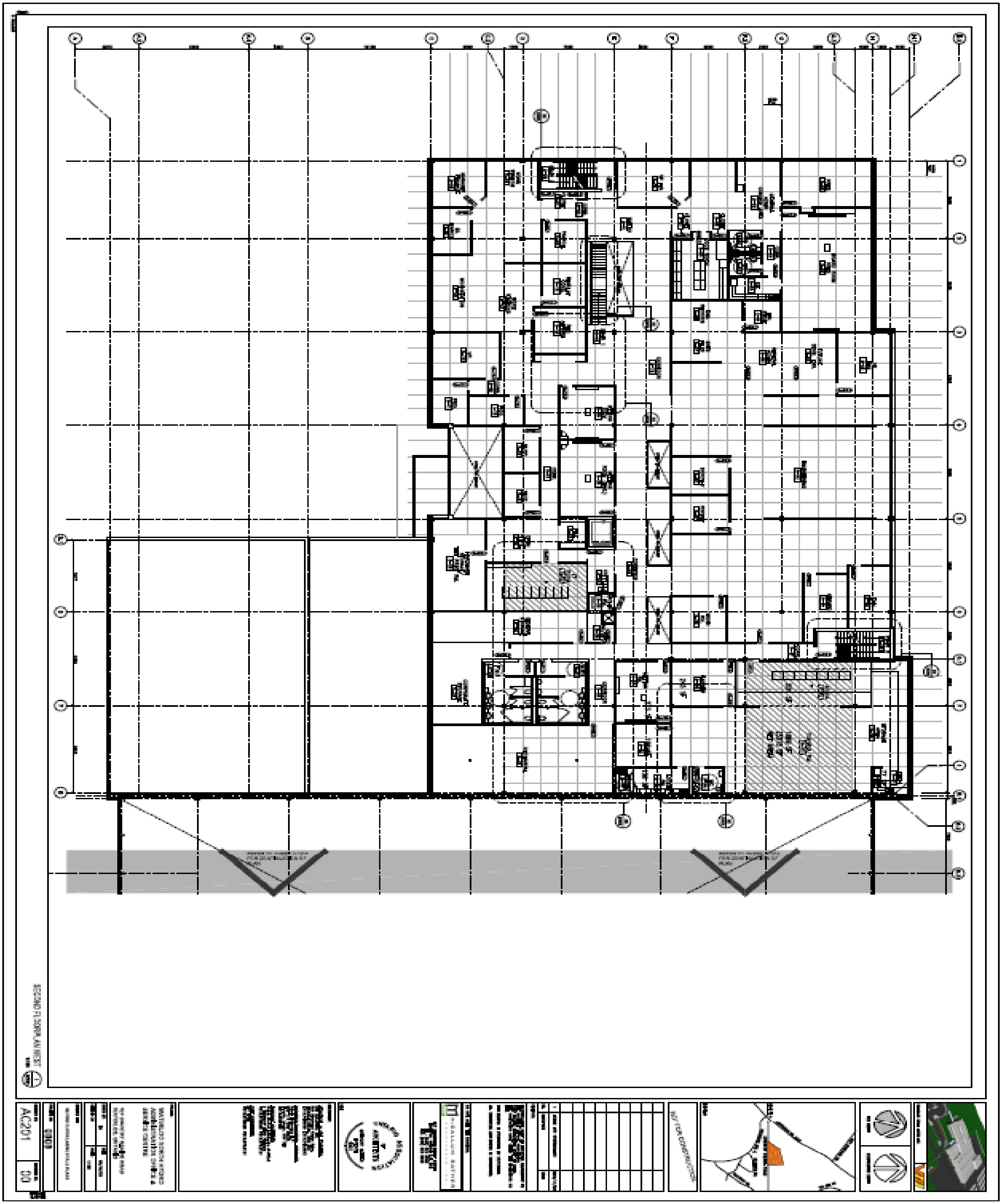
USGBC. (2005). *Leadership in Energy and Environmental Design (LEED) v2.2.* Washington DC: United States Green Building Council.

Walton, G. N., & Dols, W. S. (2006). *CONTAM 2.4 User Guide and Program Documentation.* Gaithersburg: National Institute of Standards and Technology.

APPENDIX A

Natural Ventilation Case Study Building Floor Plans


FIRST FLOOR PLAN WEST
WATERLOO NORTH HYDRO ADMINISTRATION OFFICE & SERVICE CENTRE
526 COUNTRY SQUIRE ROAD WATERLOO, ONTARIO
NOT FOR CONSTRUCTION
AC101
0909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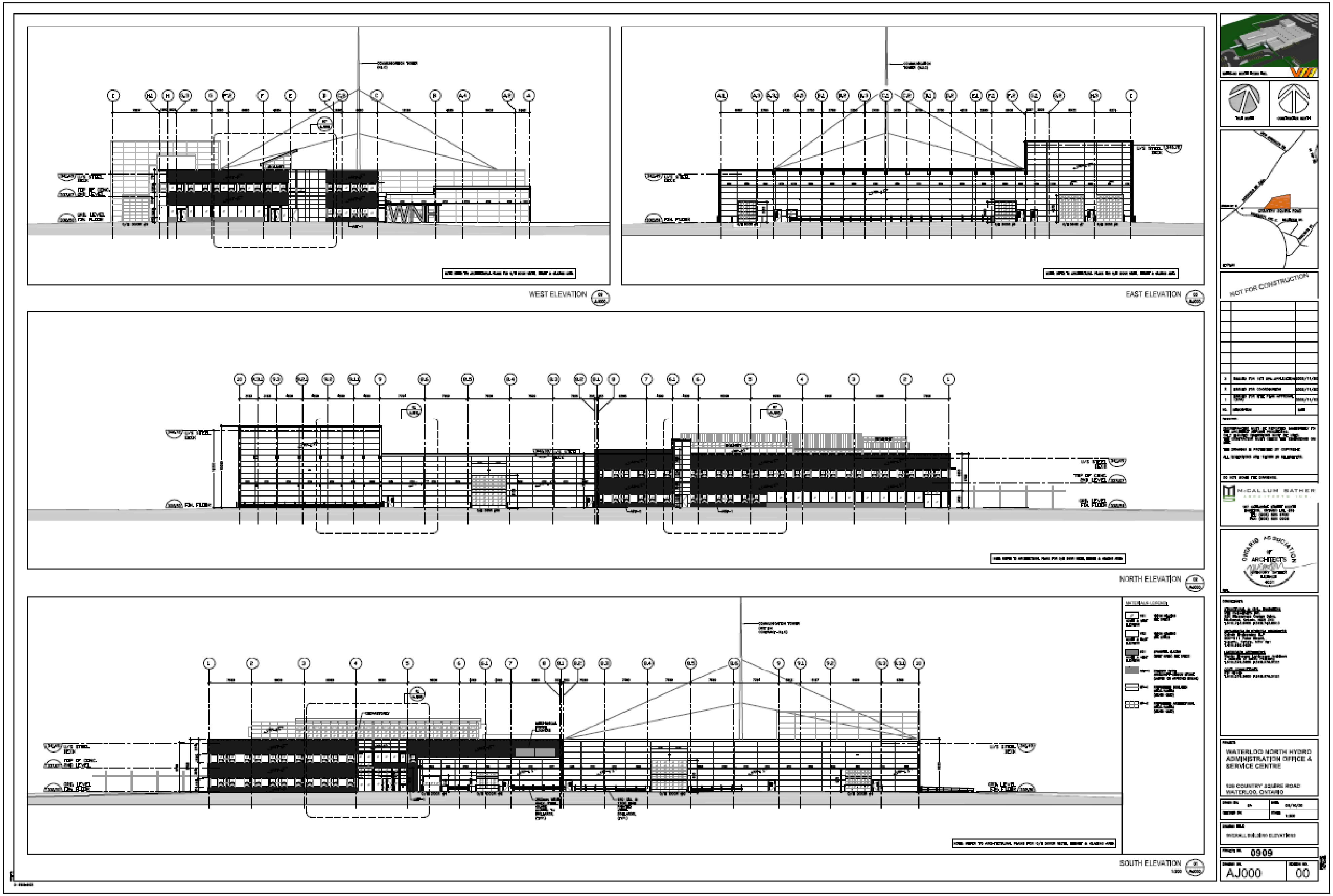
NOT FOR CONSTRUCTION


WEST ELEVATION
EAST ELEVATION
NORTH ELEVATION
SOUTH ELEVATION
NOT FOR CONSTRUCTION
ARCHITECTS
WATERLOO NORTH HYDRO ADMINISTRATION OFFICE & SERVICE CENTRE
WATERLOO, ONTARIO
0909
AJ000
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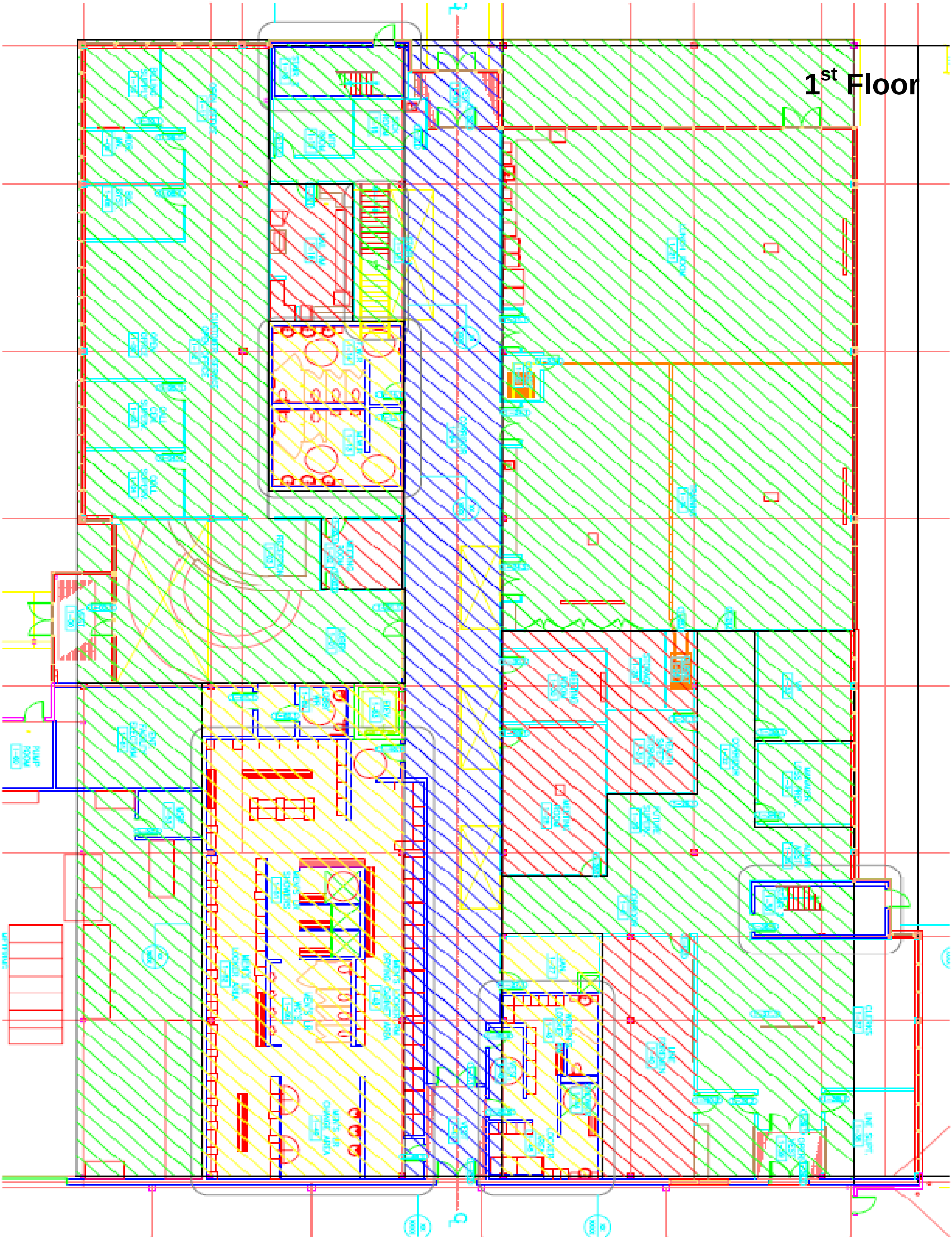
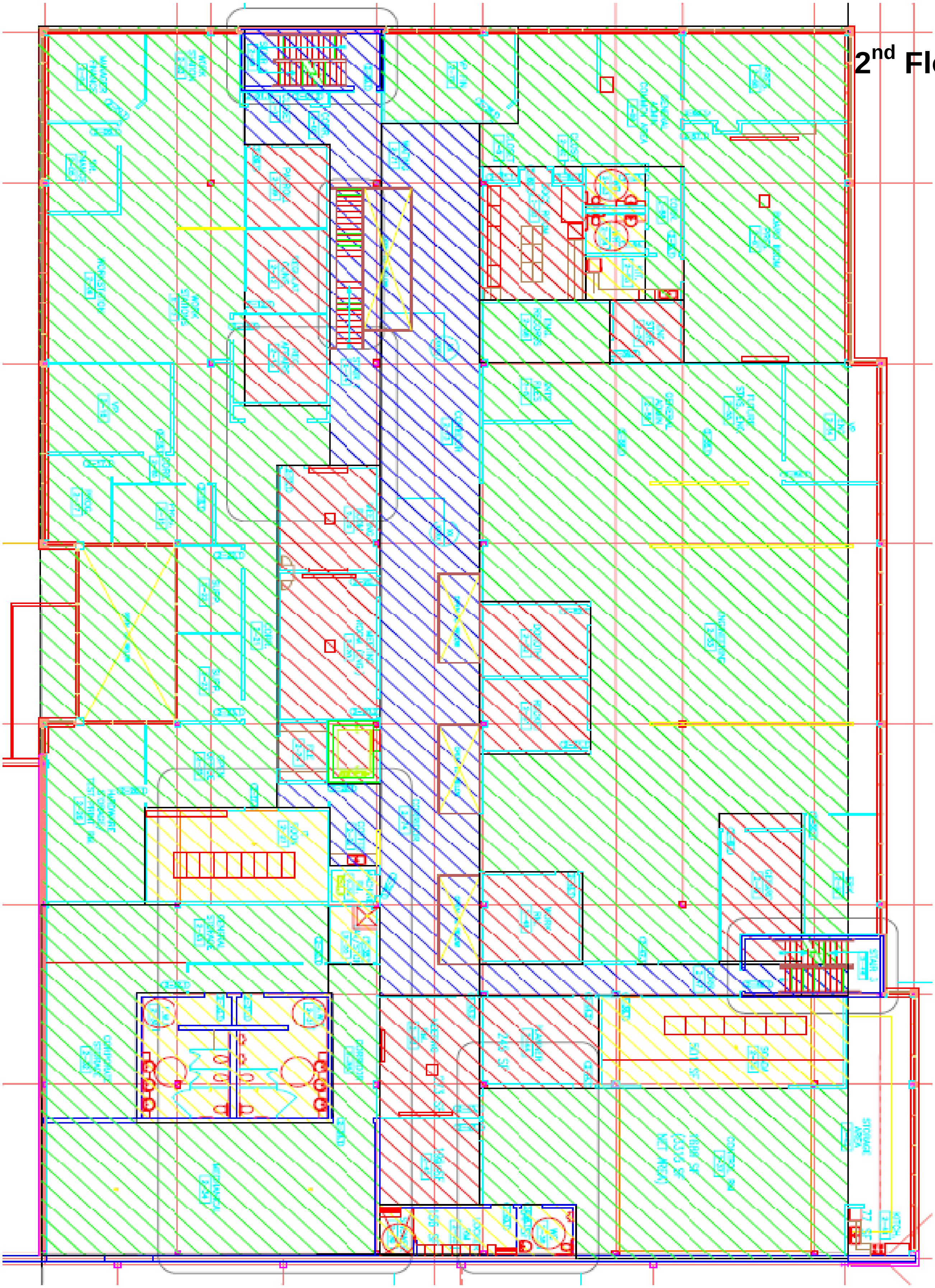

1st Floor

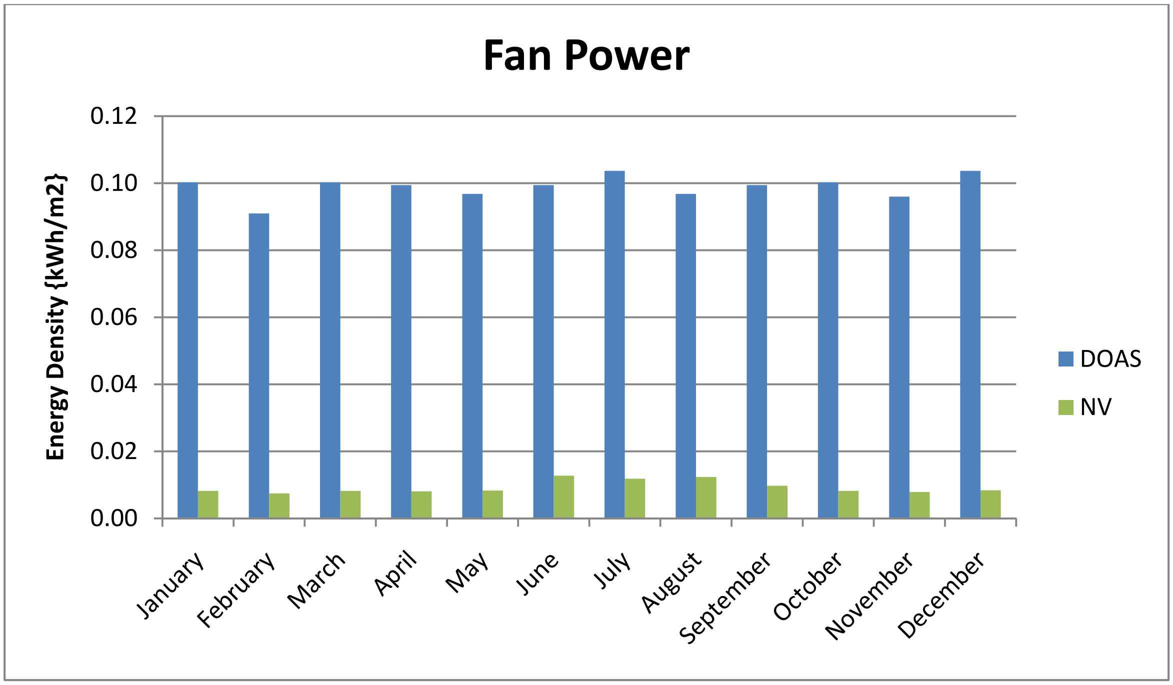
2nd Floor

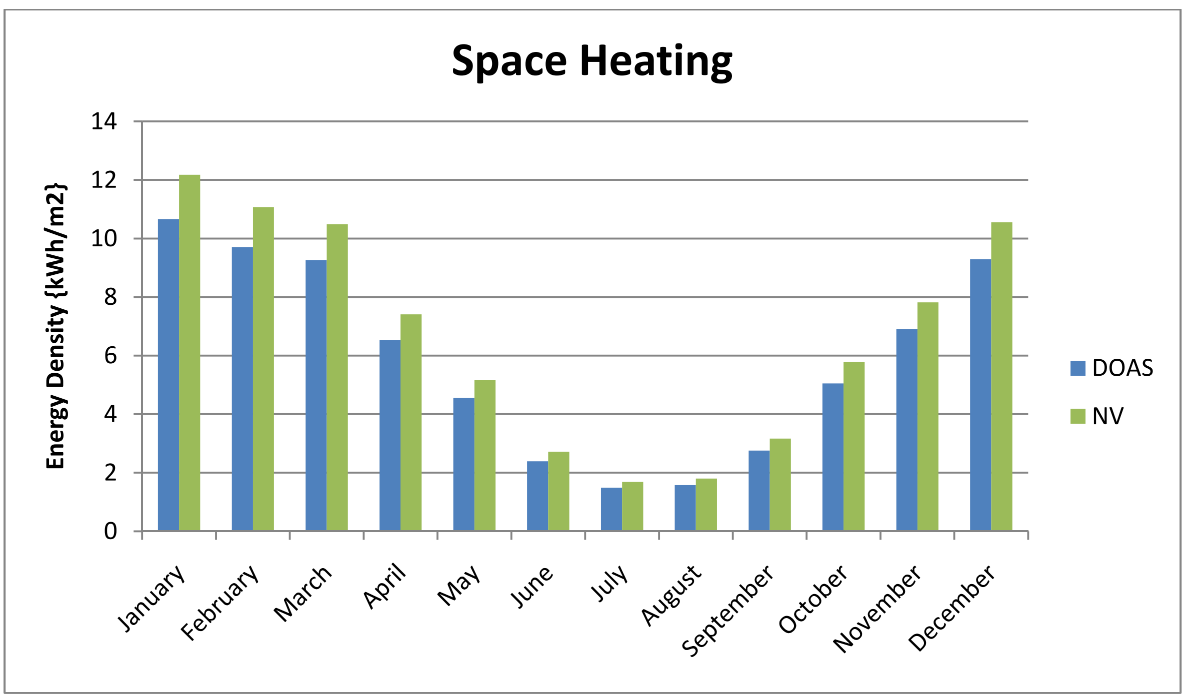


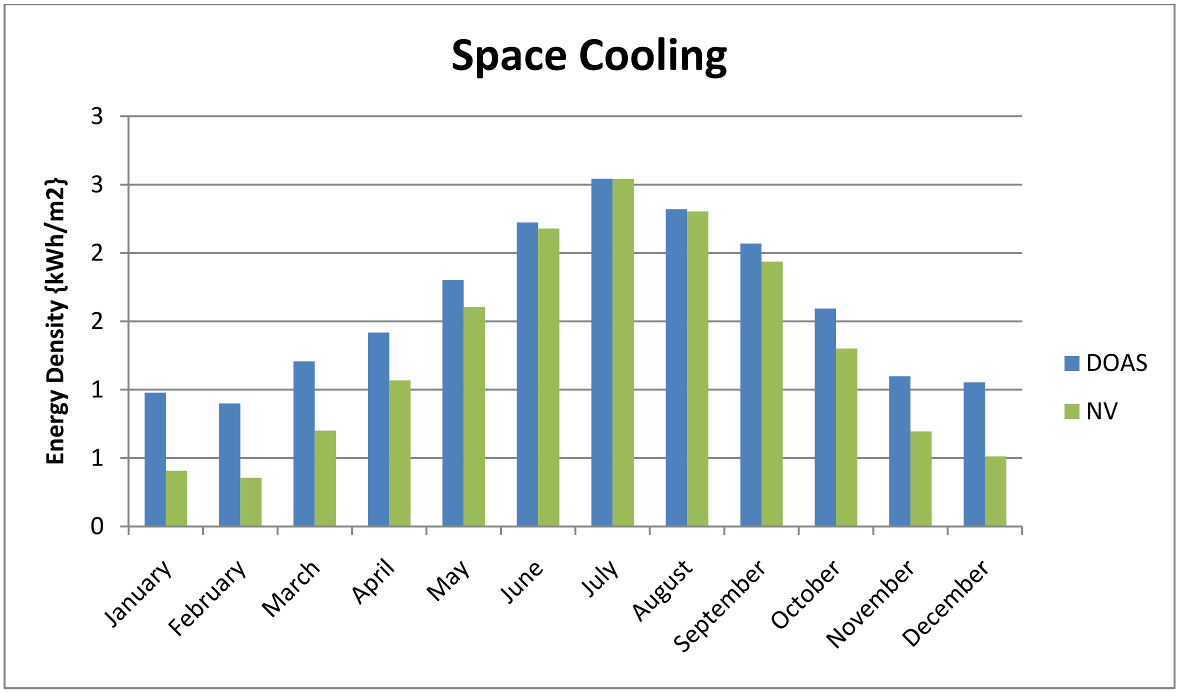
APPENDIX B

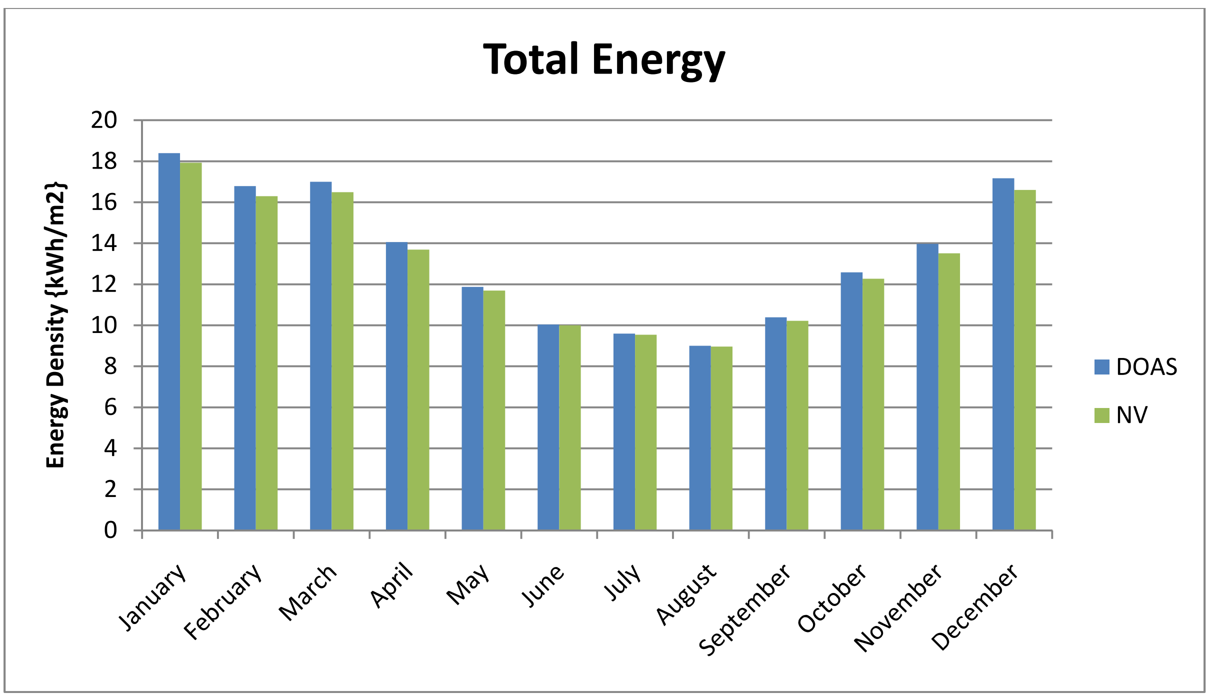
Case Study Plots

B.1 NV All Hours, Windows Fully Open

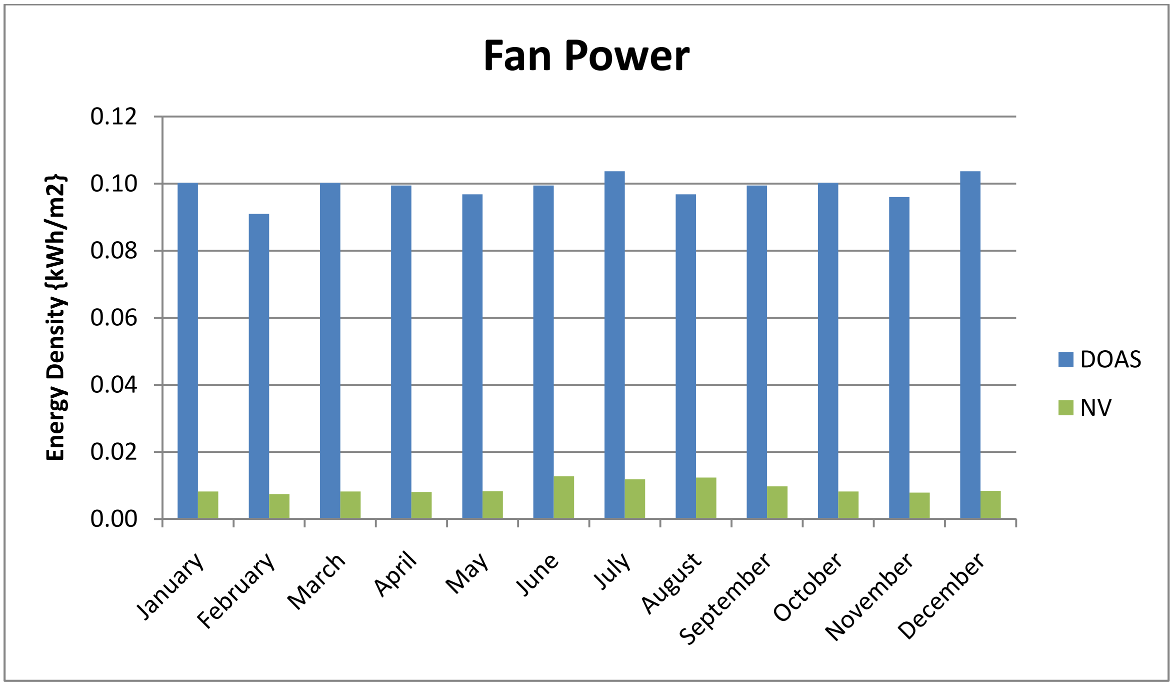


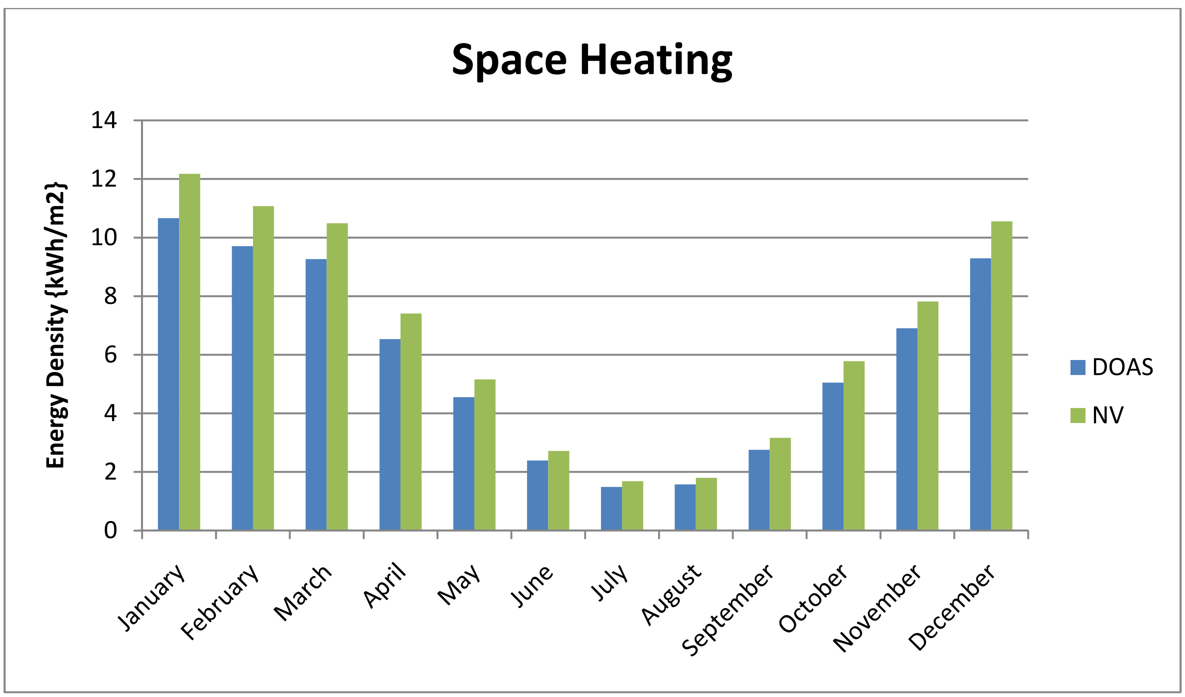


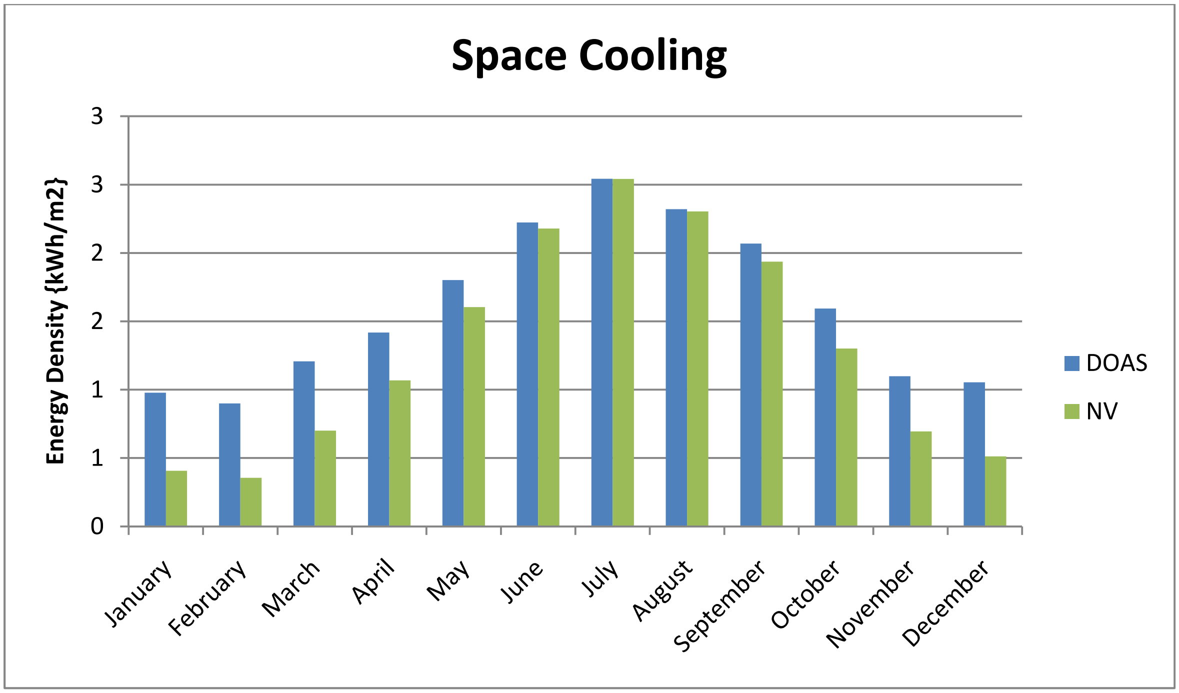

Space Cooling
Energy Density {kWh/m2}
3
3
2
2
1
1
0
January
February
March
April
May
June
July
August
September
October
November
December
DOAS
NV


Total Energy
Energy Density {kWh/m2}
20
18
16
14
12
10
8
6
4
2
0
January
February
March
April
May
June
July
August
September
October
November
December
DOAS
NV

B.2 NV All Hours, Windows Optimally Open






Space Cooling
Energy Density {kWh/m2}
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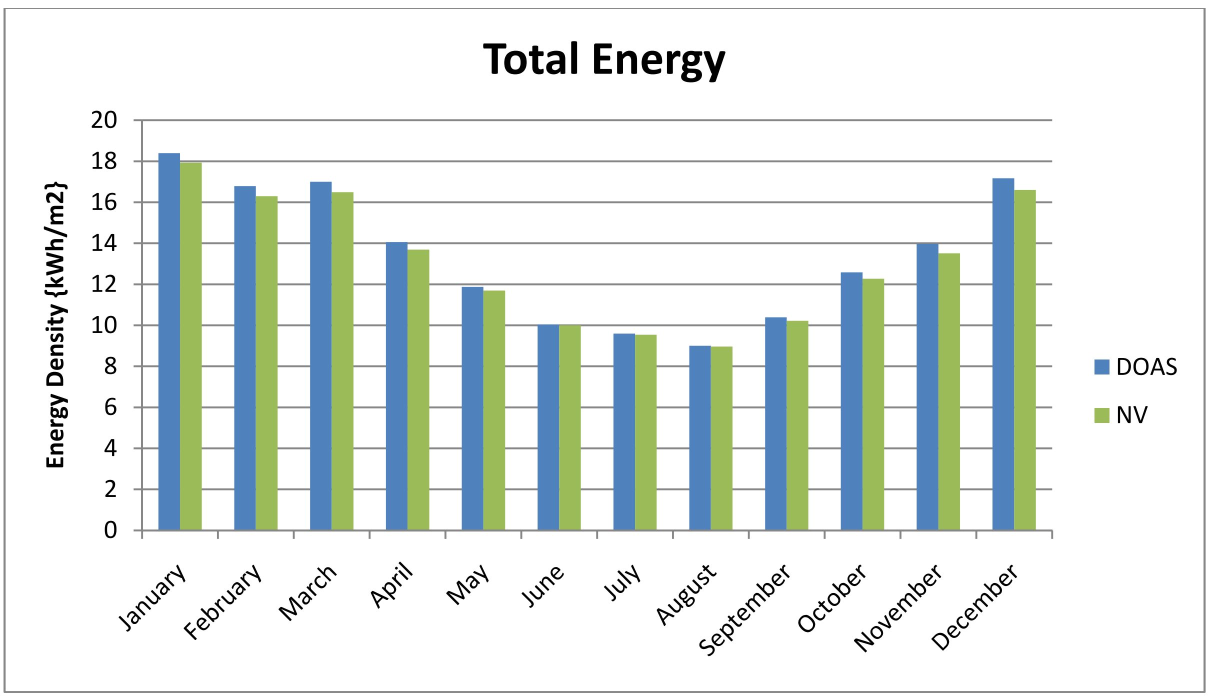
December
DOAS
NV


Total Energy
Energy Density {kWh/m2}
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July
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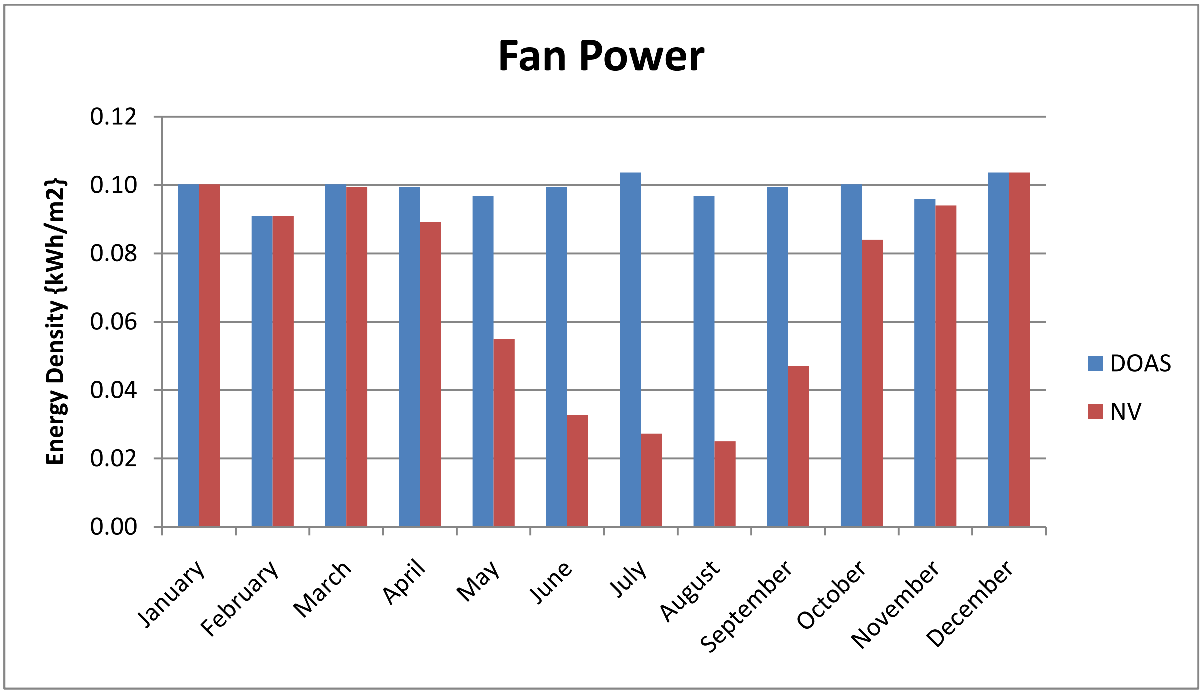
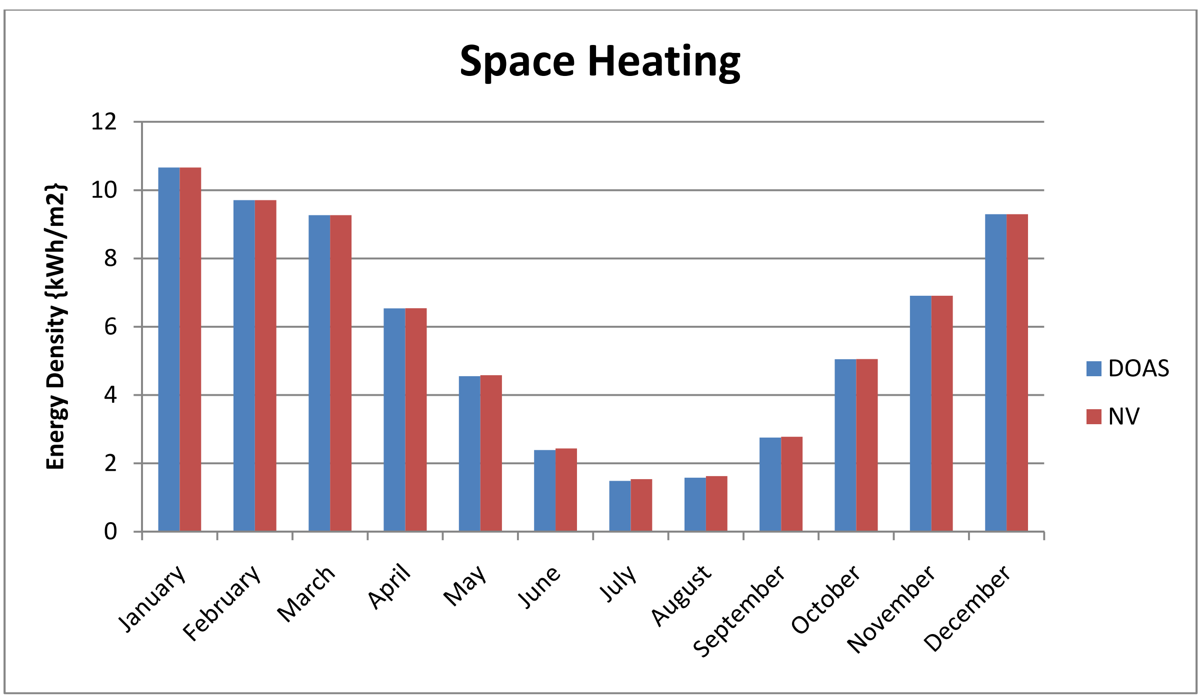
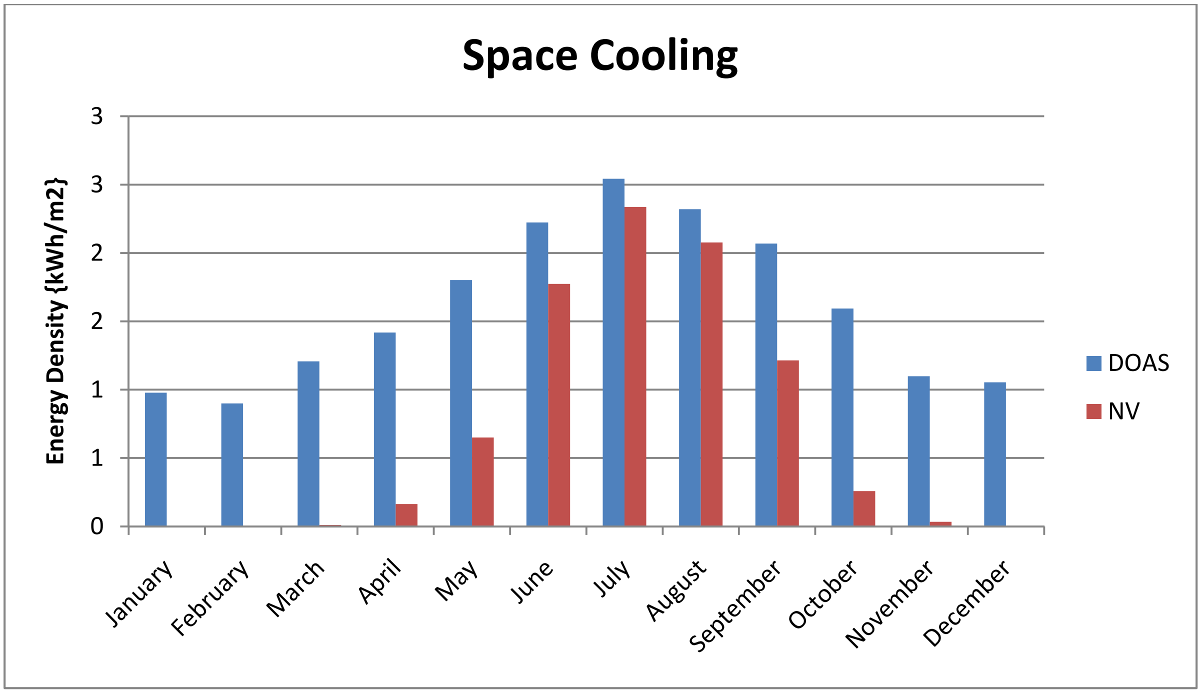
September
October
November
December
DOAS
NV

B.3 HV, Windows Fully Open







Space Cooling
Energy Density {kWh/m2}
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DOAS
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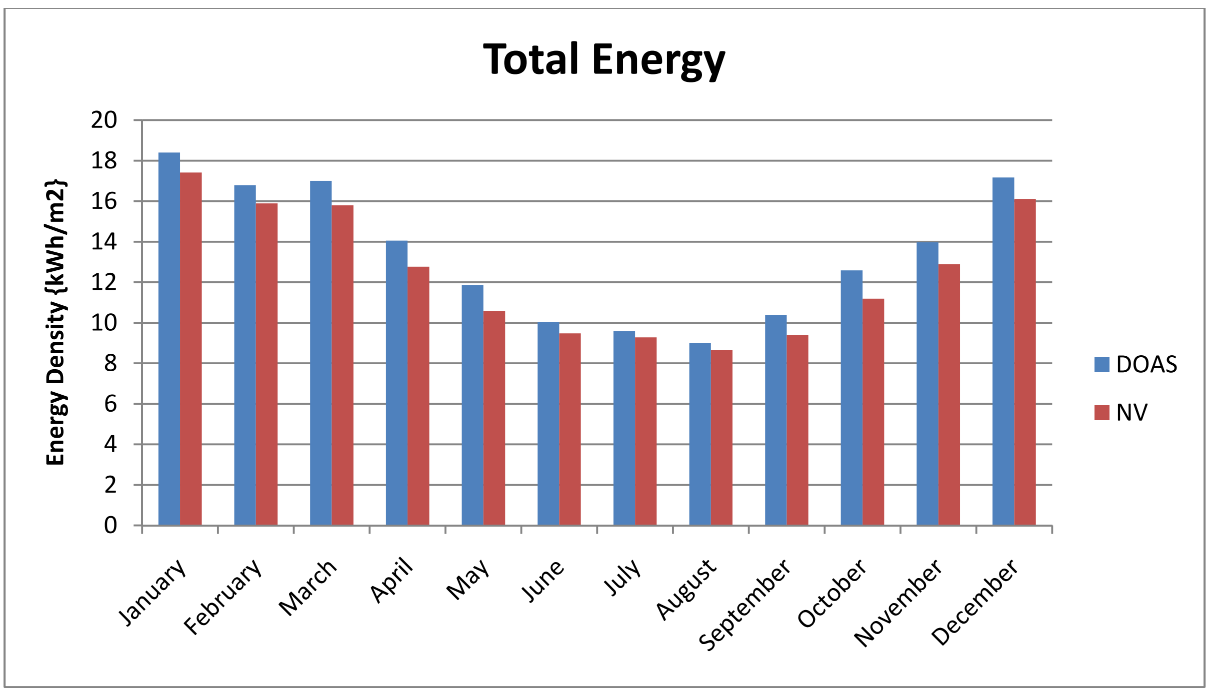

Total Energy
Energy Density {kWh/m2}
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October
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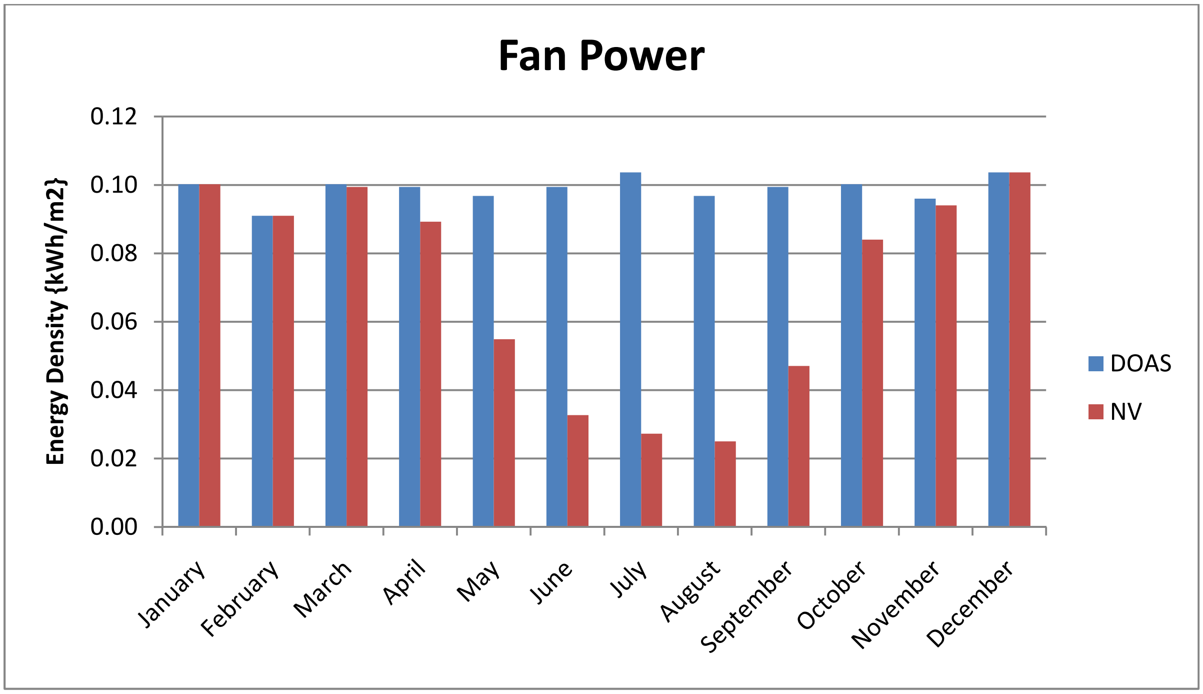
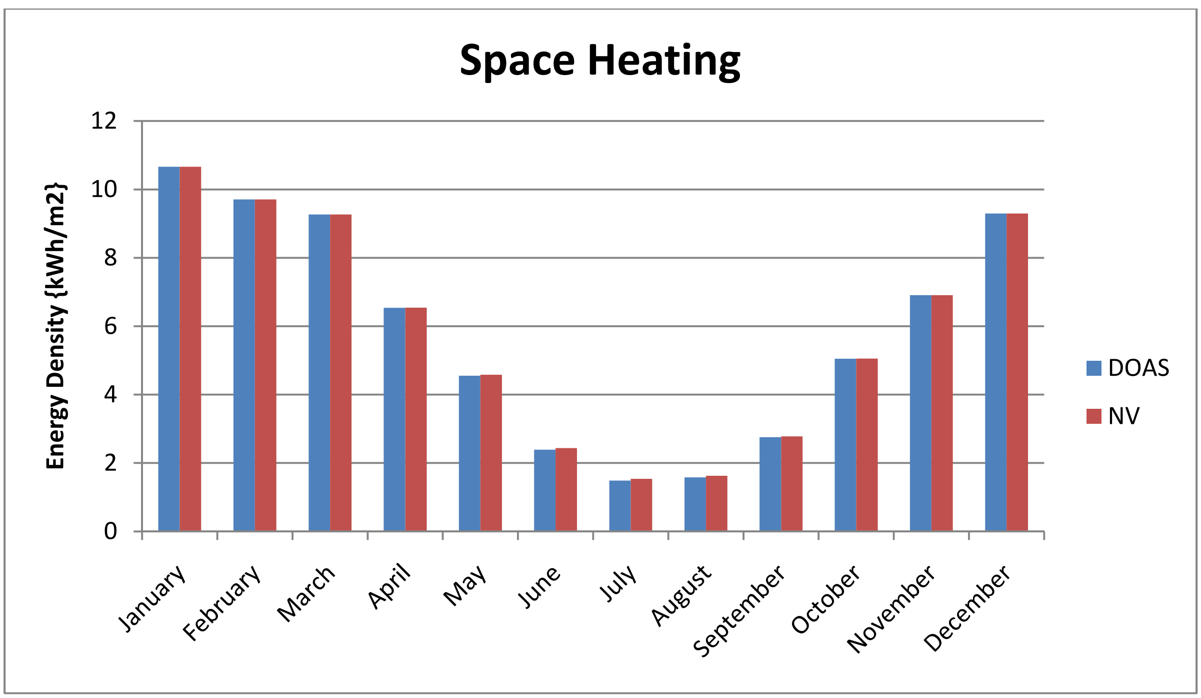
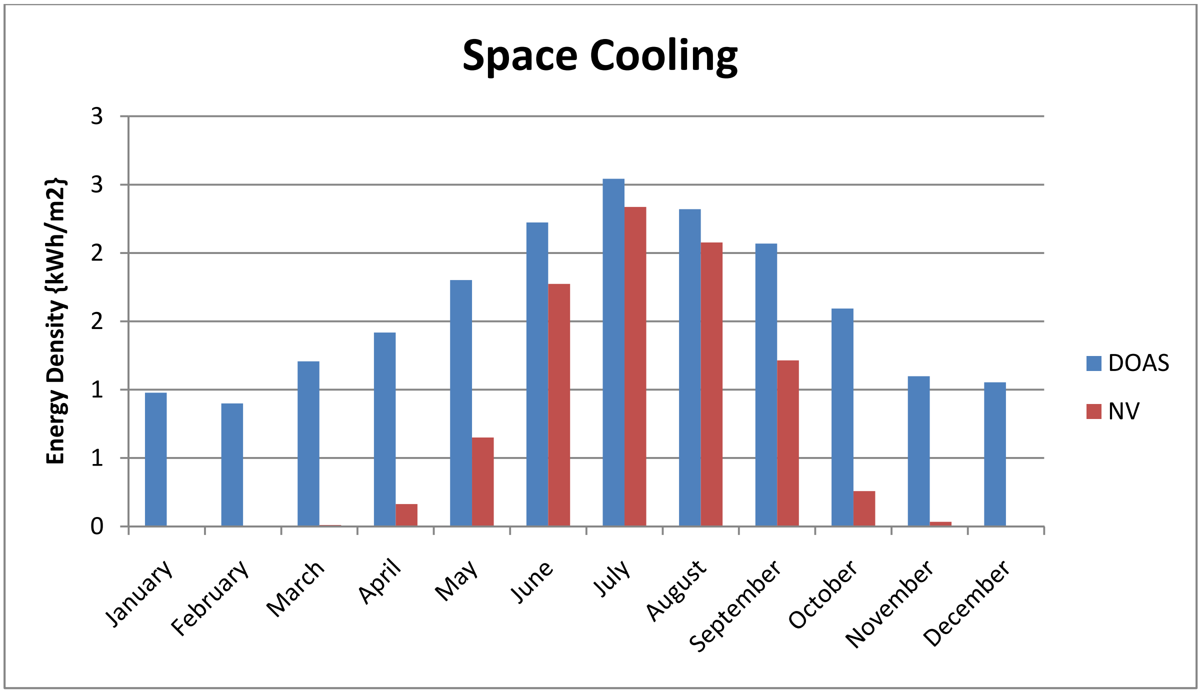
December
DOAS
NV

B.4 HV, Windows Optimally Open






Space Cooling
Energy Density {kWh/m2}
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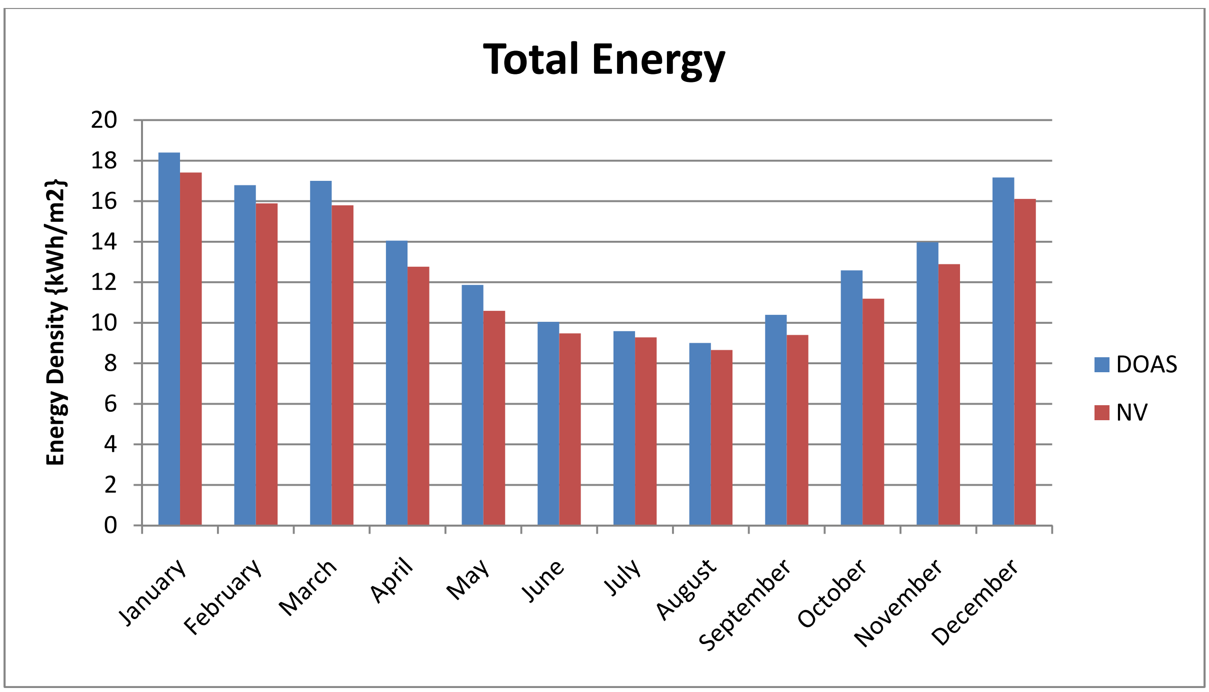
DOAS
NV


Total Energy
Energy Density {kWh/m2}
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November
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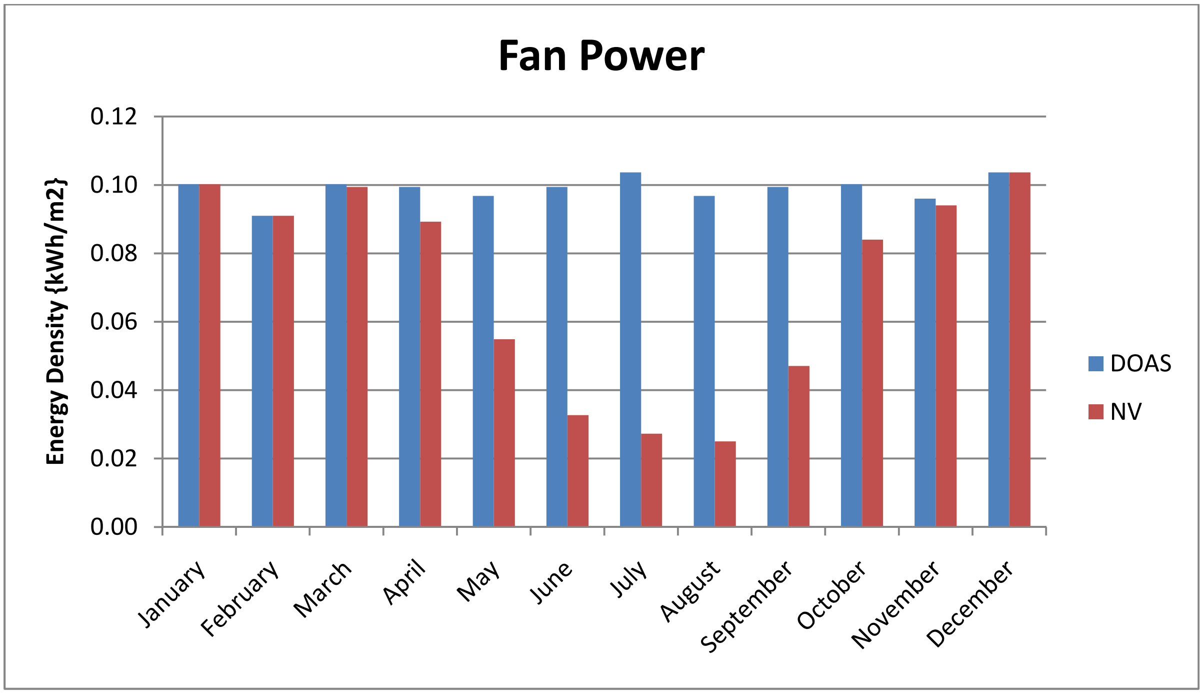
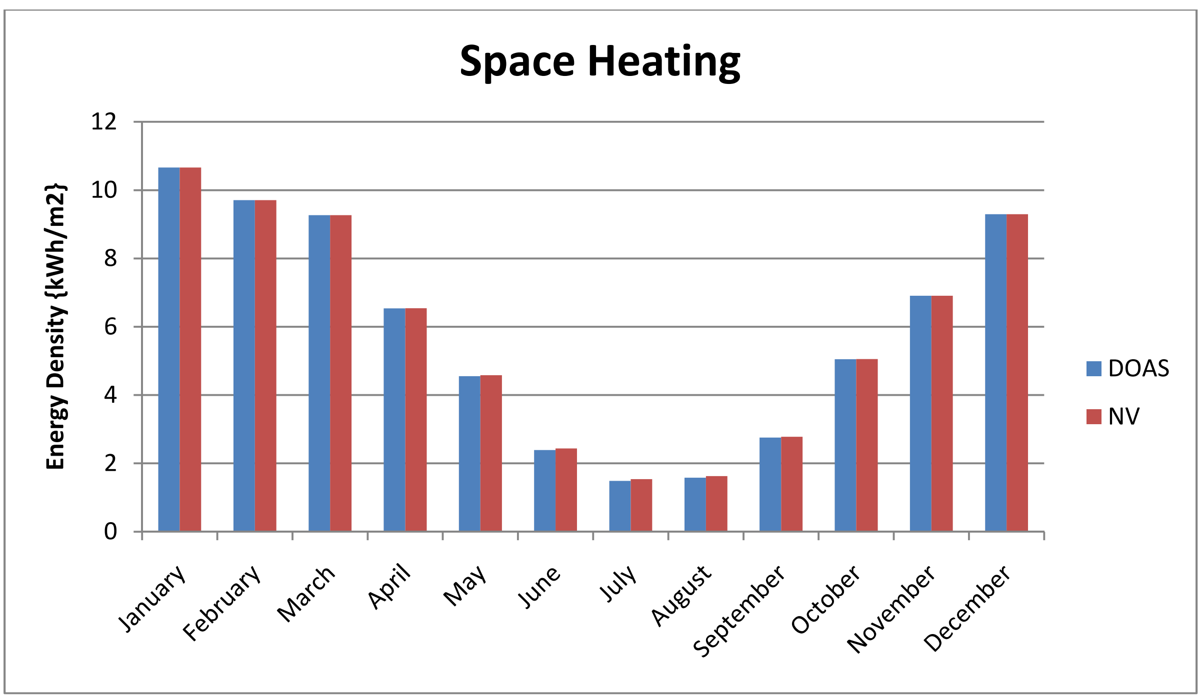
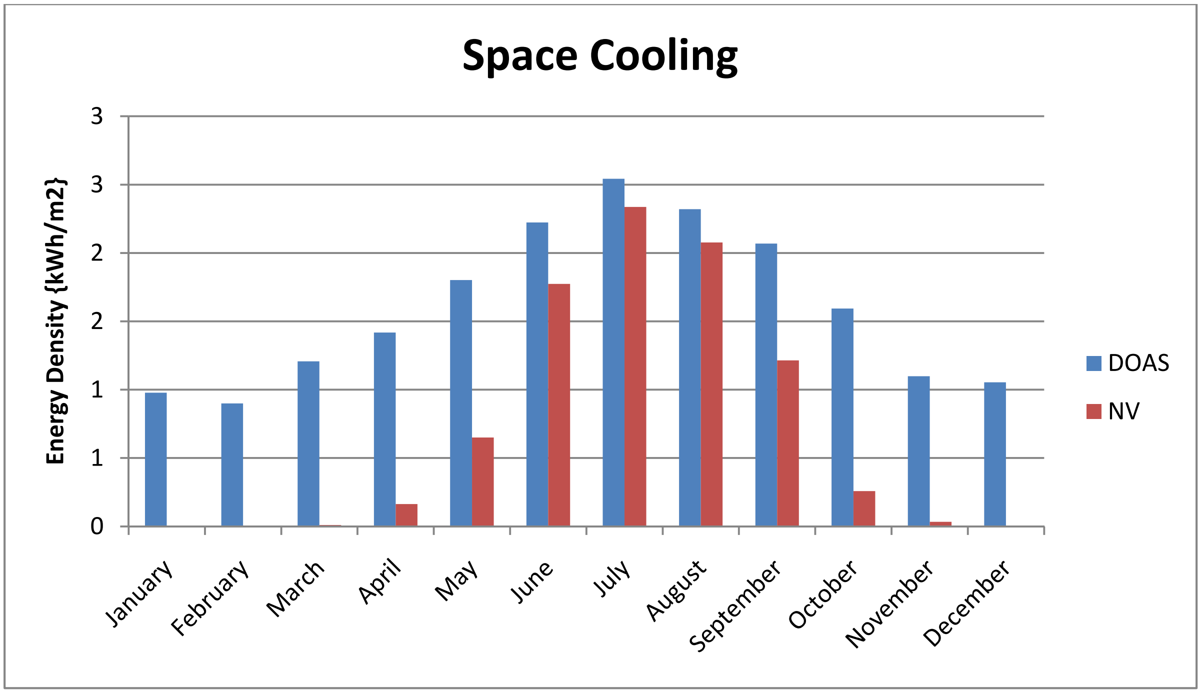
DOAS
NV

B.5 HV, Free Cooling






Space Cooling
Energy Density {kWh/m2}
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January
February
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April
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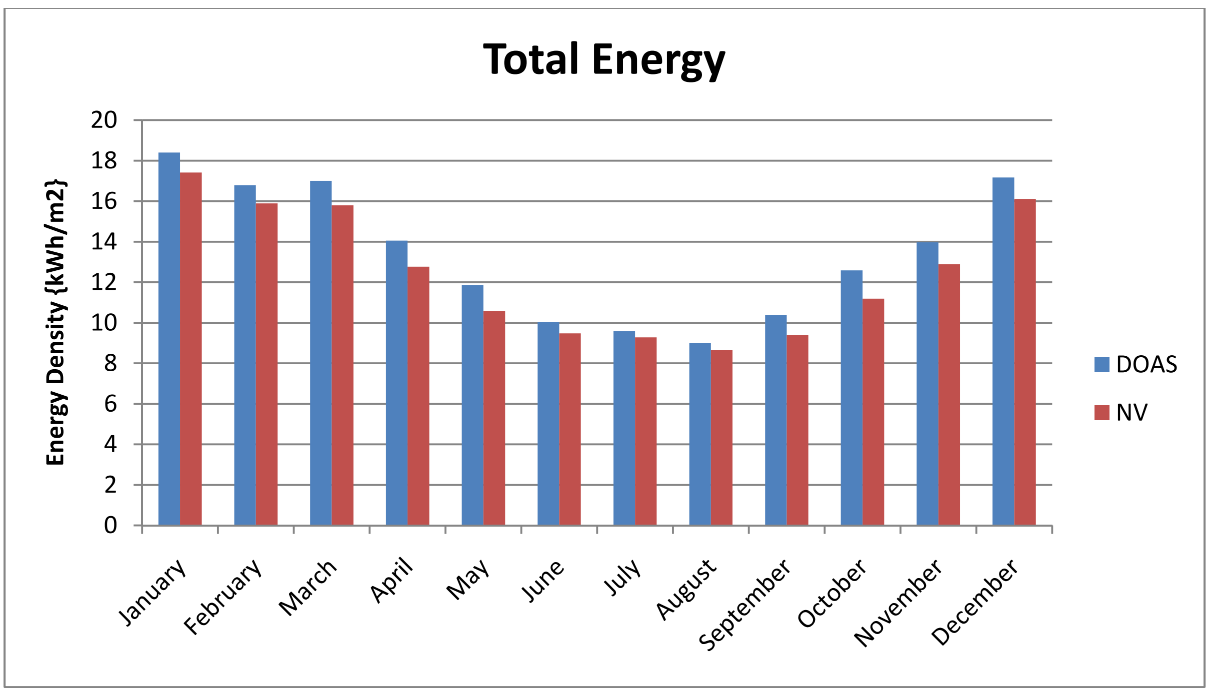
July
August
September
October
November
December
DOAS
NV


Total Energy
Energy Density {kWh/m2}
20
18
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14
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8
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June
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August
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October
November
December
DOAS
NV